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A Holistic Analysis of the Long-Term Challenges & Potential Benefits of the Green Roof, Solar PV Roofing, and GRIPV Roofing Markets in Orlando, Florida

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A HOLISTIC ANALYSIS OF THE LONG-TERM CHALLENGES & POTENTIAL BENEFITS OF THE GREEN ROOF, SOLAR PV ROOFING, AND GRIPV ROOFING MARKETS IN ORLANDO, FLORIDA

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ABSTRACT

Green roofs and roof-mounted solar PV arrays have a wide range of environmental and economic benefits, including significantly longer roof lifetimes, reductions in urban runoff, mitigation of the urban heat island (UHI) effect, reduced electricity demand and energy dependence, and/or reduced emissions of greenhouse gases (GHGs) and other harmful pollutants from the electricity generation sector. Consequently, green roofs and solar panels have both become increasingly popular worldwide, and promising new research has emerged for their potential combination in Green Roof Integrated Photovoltaic (GRIPV) roofing applications. However, due to policy resistance, these alternatives still have marginal market shares in the U.S., while GRIPV research and development is still severely limited today. As a result, these options are not yet sufficiently widespread in the United States as to realize their full potential, particularly due to a variety of policy resistance effects with respect to each specific alternative. The steps in the System Dynamics (SD) methodology to be used in this study are summarized as follows. First, based on a comprehensive review of relevant literature, a causal loop diagram (CLD) will be drawn to provide a conceptual illustration of the modeled system. Second, based on the feedback relationships observed in this CLD, a stock-flow diagram (SFD) will be developed to form a quantitative model. Third, the modeled SFD will be tested thoroughly to ensure its structural and behavioral validity with respect to the modeled system in reality using whatever real world data is available. Fourth, different policy scenarios will be simulated within the model to evaluate their long-term effectiveness. Fifth, uncertainty analyses will be performed to evaluate the inherent uncertainties associated with the analyses in this study.

Finally, the results observed for the analyses in this study and possible future research steps will be discussed and compared as appropriate.

Dedicated to all of my friends and family, and especially to my mother, **Yolanda Forero-Kelly**, whose invaluable support, guidance, and wisdom have helped shape my entire academic career.

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In addition, I wish to thank all of my family and friends for continuously supporting me throughout my time at UCF and for helping me to grow as a person and as a student.

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Green Roof Integrated Photovoltaic…………………………………………………..GRIPV

Heating, Ventilation, & Air Conditioning……………………………………………..HVAC

Hydrogen Vehicle and Infrastructure Simulator for Integrated and Operational Transportation Networks……………………………………………………………………………..H_2VISION

Landscape Research, Development, and Construction Society………………………………..FLL

National Resources Defense Council…………………………………………………….NRDC

National Renewable Energy Laboratory………………………………………………….NREL

Operation and Maintenance……………………………………………………………..O&M

Overall Cooling Effect…………………………………………………………………...OCE

Photovoltaic……………………………………………………………………………..PV

Qualifying Area Randomizer……………………………………………………………QAR

Soil Conservation Service……………………………………………………………...SCS

Stock-Flow Diagram……………………………………………………………………...SFD

Storm Water Management Model………………………………………………………SWMM

Surface Urban Heat Island………………………………………………………………SUHI

System Dynamics………………………………………………………………………….SD

United States Census Bureau…………………………………………………………...USCB

United States Department of Agriculture………………………………………………USDA

United States Department of Energy……………………………………………………DOE

United States Environmental Protection Agency………………………………………...EPA

United States General Services Administration……………………………………….GSA

University of Central Florida……………………………………………………………UCF

Urban Heat Island………………………………………………………………………...UHI

CHAPTER ONE (1) :: INTRODUCTION

1.1 Background

This section will provide a brief overview of background information concerning each of the specific sub-topics to be covered in this study. These sub-topics include:

1.1.1 Urban Runoff,

1.1.2 The Urban Heat Island (UHI) Effect

1.1.3 Energy Security,

1.1.4 Greenhouse Gas (GHG) Emissions,

1.1.5 Green Roofs,

1.1.6 Solar Energy, and

1.1.7 GRIPV Systems.

Additional sections have also been included to provide a brief summary of System Dynamics (SD) modeling as it applies to this study (Section 1.1.8), as well as an overview of the study area to be considered for purposes of this research (Orlando, F.L.), including relevant characteristics with respect to both runoff, temperature, energy demand and production, and GHG emissions as applicable to this study (Section 1.1.9).

1.1.1 Urban Runoff

In general, *surface runoff* (a.k.a. *overland flow*) is defined as the portion of the total water flow rate over a watershed from precipitation and/or other nearby sources that is not absorbed into the soil of the watershed via infiltration or evaporated into the atmosphere via evapotranspiration, which is consequently allowed to flow freely over the ground surface before ultimately being discharged from the watershed to other nearby areas and/or bodies of water (Mays 2010). As demonstrated visually in Figure 1, this surface runoff is usually kept to a relative minimum (~10%) in purely natural environments, where virtually all of the landscape in the watershed consists of pervious soils and local vegetation that can readily absorb water and provide a significantly high capacity for infiltration and transpiration, respectively. Conversely, as the urbanization of the watershed in question increases, the percentage of impervious surfaces in the watershed also increases and leaves less space available for local vegetation, making it increasingly difficult for water to be diverted via infiltration or evapotranspiration and thus greatly increasing the runoff discharge from the watershed (from ~10% to as much as ~55%). These significantly larger runoff flows in urban areas as opposed to those in less urbanized areas are commonly referred to as *urban stormwater runoff* or simply *urban runoff*.

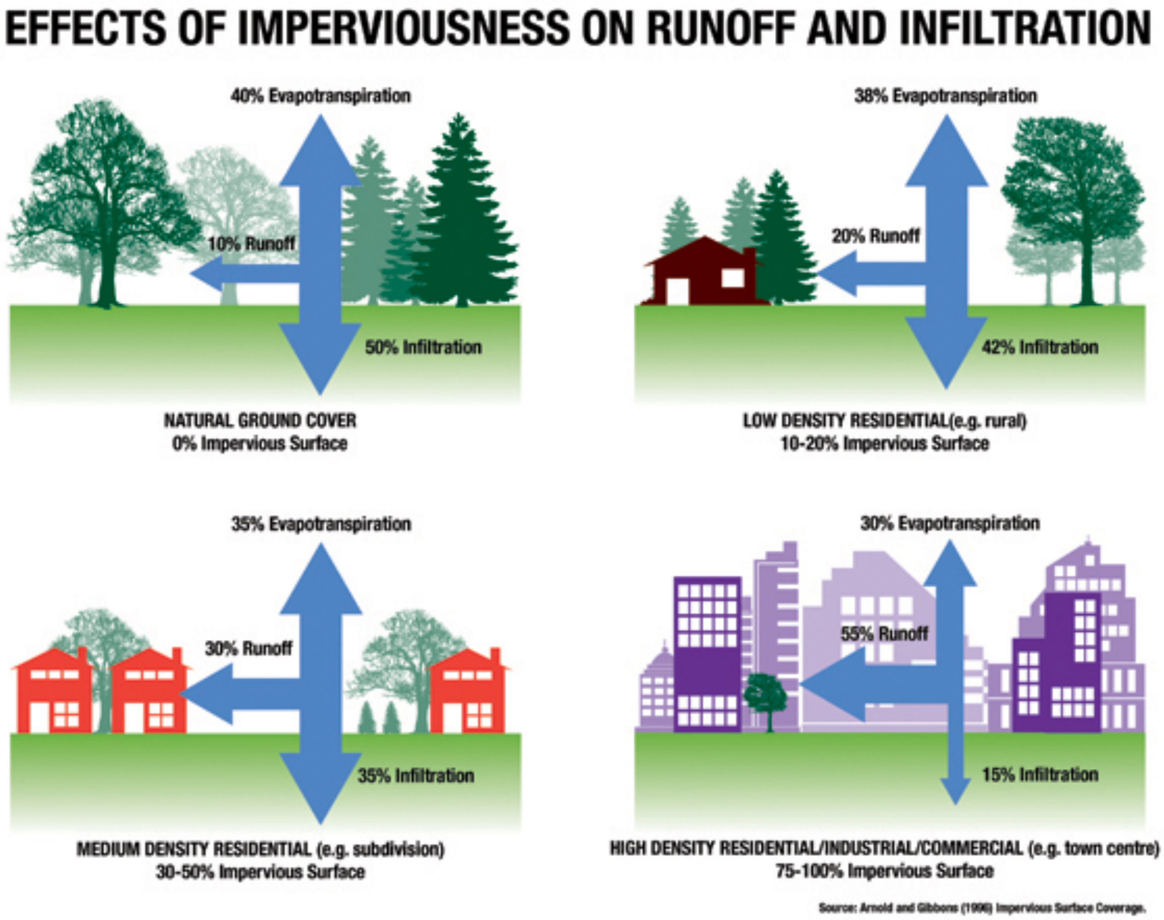


Figure 1: Comparison of Runoff Percentages for Different Degrees of Urbanization

(City of Newburgh CAC 2015)

Surface runoff in and of itself is a natural part of the water cycle and rarely results in any significant negative impacts in a typical natural landscape, but excessive amounts of urban runoff can have a wide variety of adverse impacts on human health, local ecosystems, and the overall aesthetic quality of a community (Lehner et al. 1999; Yannopoulos et al. 2013). These negative impacts are typically linked, directly or indirectly, to two primary impacts of urban runoff.

- The significantly high flow rates associated with urban runoff can lead to the increased severity and frequency of floods in an urban watershed: an effect generally known as *urban flooding*. Urban flooding accelerates the erosion of soils and streams, resulting in significant ecosystem damage as well as the increased siltation and sedimentation of the runoff water itself and of any receiving water bodies into which it is discharged. Such flooding may also result in property and/or infrastructure damage, whether from floods or from the clogging or capacity reduction of local waterways and reservoirs due to excess silt/sediment deposits, while sufficiently severe floods may even result in human fatalities.
- Urban runoff carries an increased risk of *urban stormwater pollution* because the vegetation and pervious soils that might otherwise remove pollutants from stormwater are not as readily accessible, while human activities in urban areas may leave surface runoff particularly susceptible to contamination with pesticides, heavy metals (copper, zinc, lead, etc.), and other urban pollutants that might otherwise pose no significant threat to runoff water quality. Any such pollutants in runoff water may then contaminate any water bodies and drinking water supply sources into which the runoff may be discharged, resulting in potentially serious impacts on human health and on local ecosystems and wildlife.

These environmental impacts of urban runoff may lead to subsequent societal and economic impacts as well. For example, aesthetic degradation and harm to local ecosystems may directly impact revenues from tourism and water-based recreation (fishing, swimming, water sports, etc.), as aesthetically impacted waters become less desirable for recreational purposes, while declines in local fish populations due to water pollution and habitat damage may make fishing in such waters less feasible. These tourism revenues and recreational activities contribute significantly to local employment opportunities and revenues in coastal areas as well as inland riverside and lakeside regions, making these economic impacts particularly devastating for communities in such regions (Lehner et al. 1999). Although water pollution from urban runoff and its subsequent socioeconomic impacts are beyond the scope of this study, it must be noted that minimizing the flow rate of the runoff itself (which is one of the main objectives of the policy solutions to be analyzed in this study) will in turn substantially reduce both of these adverse impacts.

1.1.2 Urban Heat Island Effect

The UHI effect is the tendency of urbanized areas to have noticeably higher temperatures than nearby non-urbanized areas under the same conditions, especially in the evening and late afternoon hours, as demonstrated visually in Figure 2. This study will focus in particular on the atmospheric urban heat island (AUHI) effect, which encompasses this effect with respect to air temperatures, as opposed to the much more variable surface urban heat island (SUHI) effect, which deals with surface temperatures. Although ambient atmospheric temperatures can fluctuate during any given time period due to a number of external factors (seasonal changes, weather conditions, etc.), the urbanization of a particular area can increase the average annual atmospheric temperature in that area by as much as 1.8^0F to 5.4^0F hotter in large cities than in surrounding rural areas, and can even increase temperatures by as much as 10^0C (50^0F) or more, due to a combination of key factors associated with urban areas and commonly-used urban construction materials (EPA 2008; Lazzarin et al. 2005). Such factors include, but are not necessarily limited to, the following:

- *Reduced Vegetation:* In urban areas, the plants and natural ground cover that might normally be available to provide shade and cool the surrounding atmosphere via evapotranspiration are significantly reduced, if not absent altogether, thus reducing the overall cooling capacity of the urban area and contributing to higher surface and atmospheric temperatures.
- *Urban Material Properties:* Unlike natural vegetation and ground cover, which can provide shade, dissipate heat, and reflect sunlight to such a degree that their surrounding temperature fluctuations are minimal, most conventional urban building materials (asphalt, concrete, roofing shingles, etc.) have a stronger tendency to absorb heat from the sun, as well as greater heat capacities than that of a typical natural landscape. As a result, the surface temperatures of these urban materials increase dramatically during the day as they rapidly absorb and the sun's heat and store significant amounts of heat over time, while local atmospheric temperatures increase as this heat is released later in the day and at night. This is especially true for darker-colored materials, including most conventional roofing and paving materials.
- *Urban Geometry:* As buildings and other obstructions are more tightly packed in urban areas, the resulting "urban canyons" generally tend to slow the release of heat from urban surfaces, thereby aggravating the AUHI effect by retaining heat

within the urban canyons for longer periods of time. In addition, although sufficiently tall buildings may create shade, they may also allow for the additional absorption and storage of heat in the walls of such buildings, as well as the more prolonged reflection and absorption of heat among clusters of such buildings, making the resulting increase in temperature more difficult to balance out.

- *Anthropogenic Heat Emissions:* Heat emissions from cars, air conditioners, and other common modern technologies are directly connected to human activities in one way or another. Such human activities are typically more prevalent in urban areas than in rural areas, and the additional heat emitted as a result of these activities contributes even further to the AUHI effect. This influence on the AUHI effect is beyond the scope of this study, but is worth noting nonetheless.

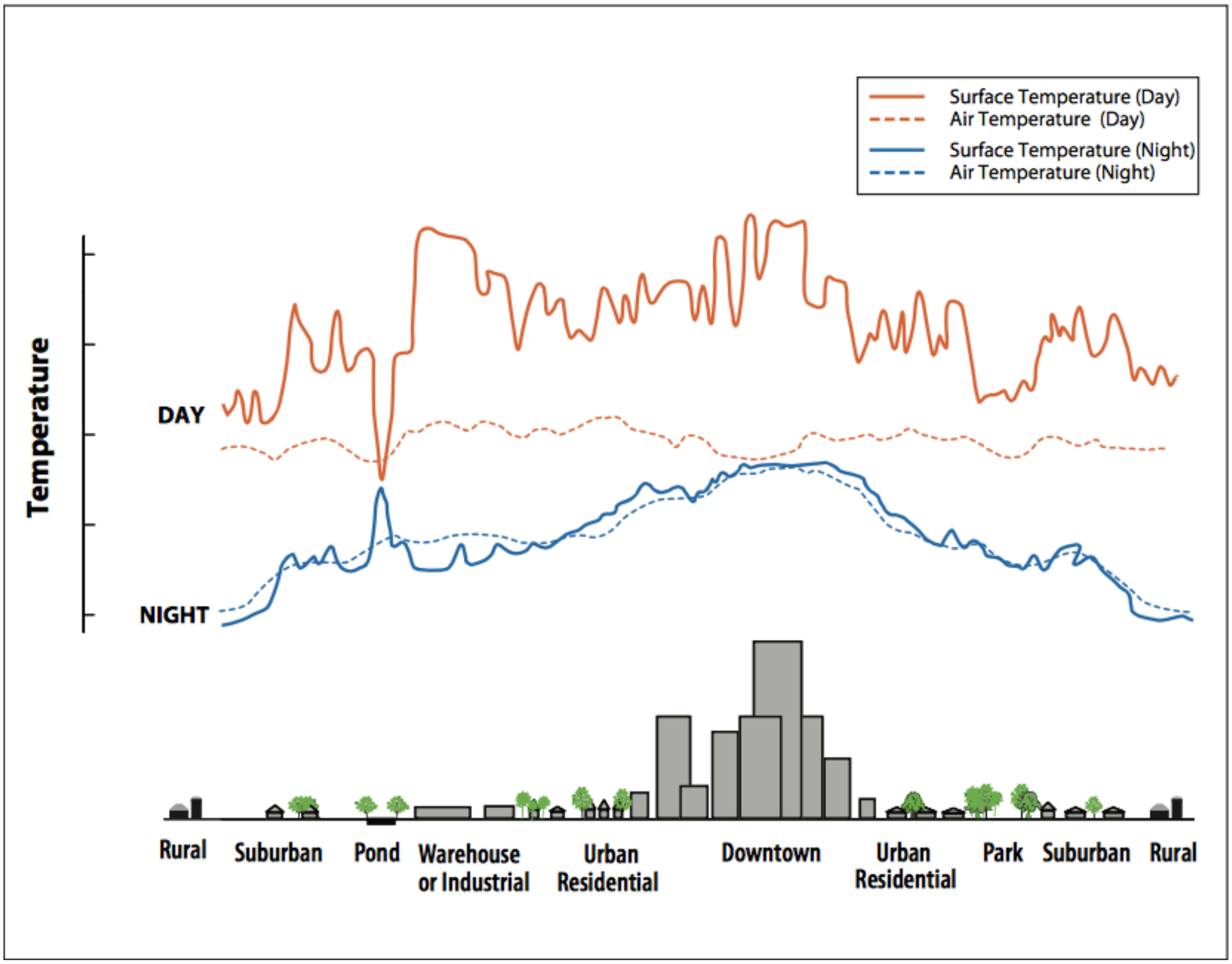


Figure 2: A Conceptual Visualization of Surface & Atmospheric Temperature Variations Over Different Types of Land Use Areas

(EPA 2008)

The UHI effect may be beneficial in the winter due to reductions in heating requirements as well as the faster melting of snow and ice on roadways, but may also have serious negative impacts on urban communities, particularly in the summer, when ambient atmospheric temperatures are already high and may increase even further in urban areas due to the UHI effect

(EPA 2008; Garrison et al. 2012). These negative impacts include, but are not limited to, the following:

- *Increased energy consumption* due to increased demand for air conditioning and other cooling activities,
- *Increased water consumption* due to additional water requirements for irrigation, drinking water, industrial water consumption/withdrawal demand, and other uses as necessary,
- *Increased air pollution and greenhouse gas emissions* as a result of the aforementioned increase in energy consumption as well as increased ground-level ozone formation rates,
- *Impacts on human health and comfort* due to the aforementioned degradations in air quality as well as the potential to exacerbate the harmful impacts of heat waves, including the possibility of contributing to respiratory difficulties, heat stroke, or even heat-related mortality, and
- *Degradation of water quality*, primarily due to thermal pollution as runoff water is warmed by hot rooftops and/or pavements and subsequently flows into local water bodies, increasing water temperatures in these water bodies and potentially endangering the aquatic ecosystems within them due to thermal stress/shock and other related impacts.

Energy consumption and greenhouse gas emissions will both be covered in this study as well, as discussed in more detail in Sections 1.1.3 and 1.1.4, respectively. All other specific adverse impacts of the UHI effect as listed above are beyond the scope of this study, but it must be noted that reductions in the atmospheric temperature increases from the UHI effect will also reduce these impacts. Furthermore, although it has been previously noted that the UHI effect may have some positive impacts in the winter, the benefits of green roofs, as discussed further in Section 1.1.5, are generally year-round and can potentially compensate for any lost wintertime benefits as the UHI effect is reduced.

1.1.3 Energy Security

For decades, the electricity generation sector in the U.S. has relied heavily on the use of fossil fuels (especially coal) for energy production and consumption. As shown in Figure 3, electricity from conventional fossil fuels (coal, natural gas, and oil) has consistently had a dominant share in the U.S. energy sector, altogether accounting for as much as 83.2% of total electricity production in 1966; although this share has gradually decreased since then, fossil fuel energy production in the U.S. is still relatively high, accounting for 67.5% of U.S. electricity production as of 2014, with coal as the consistently predominant fuel for energy production from 1960 to 2014 (World Bank Group 2016). At the same time, as shown in Figure 4, U.S. energy demand per capita increased at a relatively steady rate from 4,049.8 kWh/capita in 1960 to 13,671.1 kWh/capita in 2000, and despite this trend slowing down considerably on average since then, no consistent decreasing trend has been evident in later years (World Bank Group 2016).

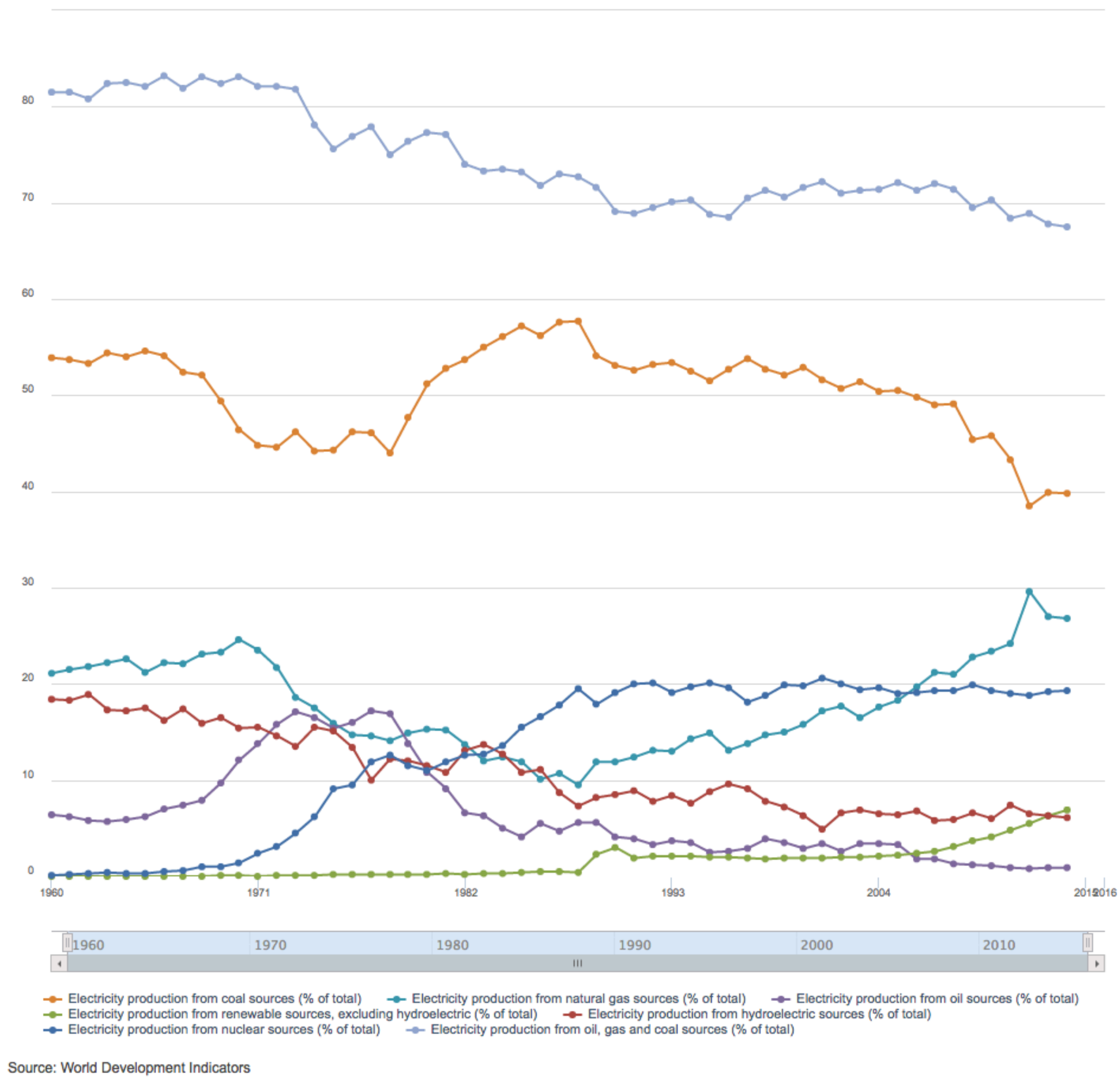


Figure 3: U.S. Electricity Production Percentages By Source From 1960 to 2014

(World Bank Group 2016)

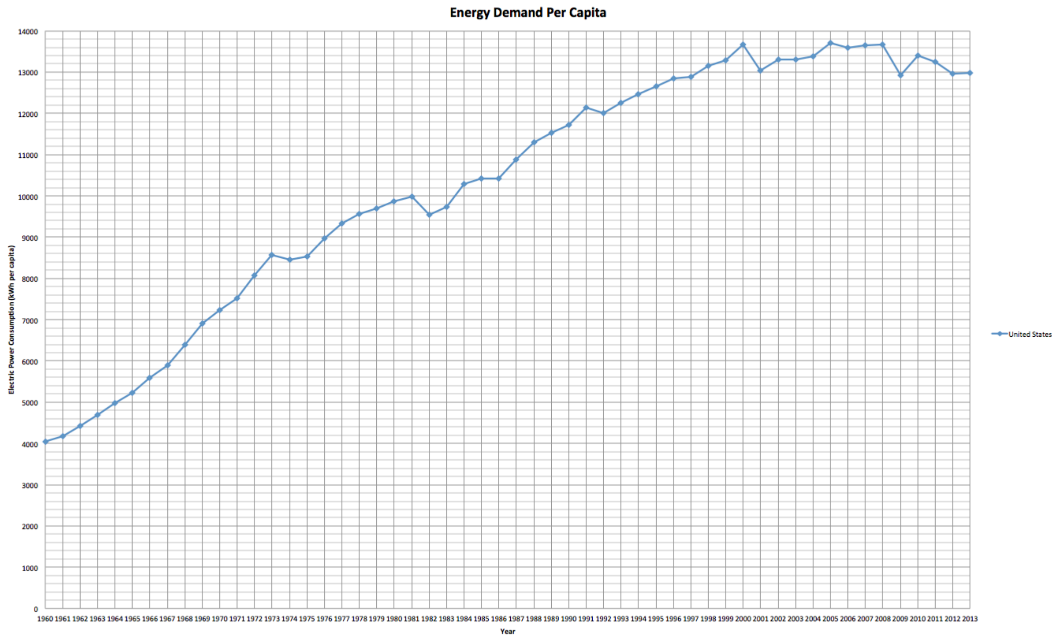


Figure 4: U.S. Energy Demand Per Capita From 1960 to 2013 (World Bank Group 2016)

This combination of a heavy dependence on fossil fuels and a historically increasing trend in energy demand per capita has led to a vicious cycle resulting in significant energy security concerns due to the various environmental and socioeconomic implications of society's dependence on fossil fuels:

- *Environmental Concerns:* The consumption of fossil fuels such as coal for electricity emits a wide range of harmful air and water pollutants, including carbon dioxide (CO_2) as discussed in more detail in Section 1.1.4, as well as sulfur dioxide (SO_2) and nitrogen oxides (NO_X) as shown in Figure 5, among other hazardous emissions. Many of these emissions can have serious adverse impacts on human health and the environment; for example, CO_2 and other GHGs are the primary contributors to anthropogenic global warming and its associated environmental impacts (EPA 2016a) as discussed further in Section 1.1.4, while SO_2 (EPA 2016b) and NO_X (EPA 2016c) are both harmful to human respiratory health and can both contribute to acid rain and other environmental impacts. Although SO_2 and NO_X emissions in the U.S. have both decreased dramatically since 1990 due to increasingly stringent local and federal regulations as well as significant technological improvements in pollution treatment systems, millions of metric tons of these and various other harmful pollutants are still being emitted every year from the U.S. electric power sector and from several other important sectors in the U.S. (transportation, industrial, etc.). Furthermore, the historically increasing trend in total electricity demand in the U.S. (especially as the population increases), coupled with the electricity sector's current dependence on fossil fuels despite their adverse environmental and human health impacts, means that these environmental impacts are likely to continue to become worse over time unless future policy initiatives can reduce energy demand and/or the need for fossil fuels to supply the required energy. SO_2 and NO_X emissions are both beyond the scope of this study, but it must still be noted that, since fossil fuels are a primary source of SO_2 and NO_X emissions, reducing the need for fossil fuels will in turn reduce both of these emission types.

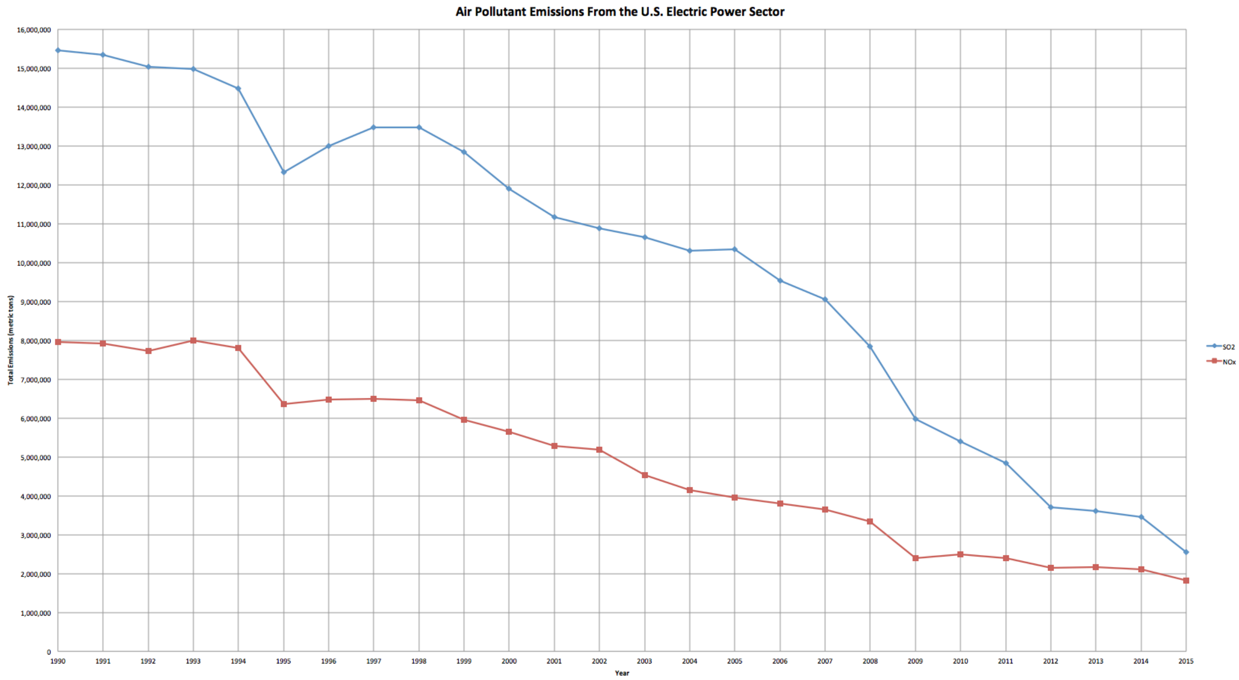


Figure 5: SO_2 and NO_X Emissions From the U.S. Energy Generation Sector from 1990 to 2015 (EIA 2016a)

- *Socioeconomic Concerns:* In addition to the above-mentioned environmental and human health concerns, the current lack of energy security in the U.S. also has potentially serious socioeconomic implications, particularly in terms of the need for fossil fuels to meet growing electricity demand levels. As the U.S. energy sector's dependence on electricity and on the fuels required to produce it increases, electricity and fuel prices in the U.S. will also increase, especially as fossil fuels (which are nonrenewable) become more and more scarce over time. Furthermore, if and when usable fossil fuel resources eventually run out, the resulting fuel shortages could be disastrous for the U.S. electric power sector and for several other sectors (transportation, industrial, etc.) that are also still heavily dependent on fossil fuels today.

In more recent years, various renewable energy resources (solar, wind, etc.) have been studied in academic research and applied in industrial practice in an effort to provide cleaner, more renewable alternatives to fossil fuel energy, thereby improving energy security by reducing the need for fossil fuel energy while also reducing the adverse environmental impacts associated with fossil fuel consumption. However, despite significant improvements in renewable energy technology in the past few decades, the use of renewable energy in today's electricity generation sector is still very limited. As previously shown in Figure 3, renewable energy (excluding hydroelectric energy) still only accounts for 6.9% of total electricity production in the U.S. as of 2014; if hydroelectric energy is included, this percentage still remains relatively low at a total of 13% (World Bank Group 2016). Therefore, this study will attempt to find a realistically feasible policy solution to maximize the long-term market penetration of a form of renewable energy infrastructure (in this case, roof-mounted solar panels and BIPV solar roofing) and its subsequent benefits with regard to energy security in addition to other benefits as applicable. Furthermore, since one of the primary hindrances to energy security today is the currently high level of energy demand (esp. energy demand per capita), this study will also analyze the potential of different alternative roofing options to reduce these energy demand levels and thus improve energy security on a holistic long-term basis.

1.1.4 GHG Emissions

Greenhouse gases (GHGs) are atmospheric gases that absorb thermal radiation from the sun and thus serve as the primary contributors to the "greenhouse effect" that maintains the natural warmth of Earth's atmosphere; without this natural greenhouse effect, the average temperature of the Earth's surface would be below the freezing point of water, and life as we know it would not be possible. Many of these GHGs (water vapor, CO_2, etc.) are already found in nature and, in a purely natural landscape, can ordinarily be maintained at natural levels through natural processes such as the absorption of CO_2 by plants. However, the burning of fossil fuels for energy production and other purposes contributes even further to GHG concentrations in the atmosphere, while increasing urbanization in many parts of the world (especially in developed countries) reduces the Earth's natural ability to regulate these atmospheric concentrations due to increasing rates of deforestation and other such activities to make way for more urban development. As a result, if total worldwide GHG emissions are not actively controlled to a sufficient degree and/or the Earth's natural regulation capacity is not sufficiently replenished, atmospheric GHG concentrations experience a continuous net increase over time and thus enhance the greenhouse effect beyond its natural levels, increasing man-made global warming and, in turn, resulting in anthropogenic global climate change (IPCC 2007), the subsequent direct and indirect impacts of which can include, but are not limited to, the following (USGCRP 2009):

- Increasing air and water temperatures,
- Rising sea levels,
- Reductions in natural ice/snow cover (glaciers, permafrost, etc.)

- Increasing frequency and intensity of storm surges, and
- Potentially serious indirect impacts of one or more of the above (drought, human health impacts, reductions in agricultural yields, etc.).

As previously noted, the consumption of fossil fuels contributes significantly to anthropogenic emissions of CO_2 and other GHGs. In the U.S., this is especially true of the electricity generation sector, which was responsible for 30.3% of all GHG emissions in the U.S. in 2014 and has historically been the country's greatest individual contributing sector to GHG emissions (EPA 2016d). As such, the U.S. electric power sector has been the subject of many recent efforts in research and policymaking to reduce GHG emissions, but as shown in Figure 8, these efforts have not yet achieved any significant long-term success. Unlike the corresponding SO_2 and NO_X emissions previously shown in Figure 6, GHG emissions from the U.S. electric power sector increased significantly from 1991 to 2007 and, as of 2014, are still considerably higher than their corresponding rates in 1990. This shows that, despite significant advances in the development and application of green infrastructure and cleaner alternatives to fossil fuel energy, more effective development and policymaking will still be required for both of these fields in the future in order to yield any significant long-term GHG emission savings.

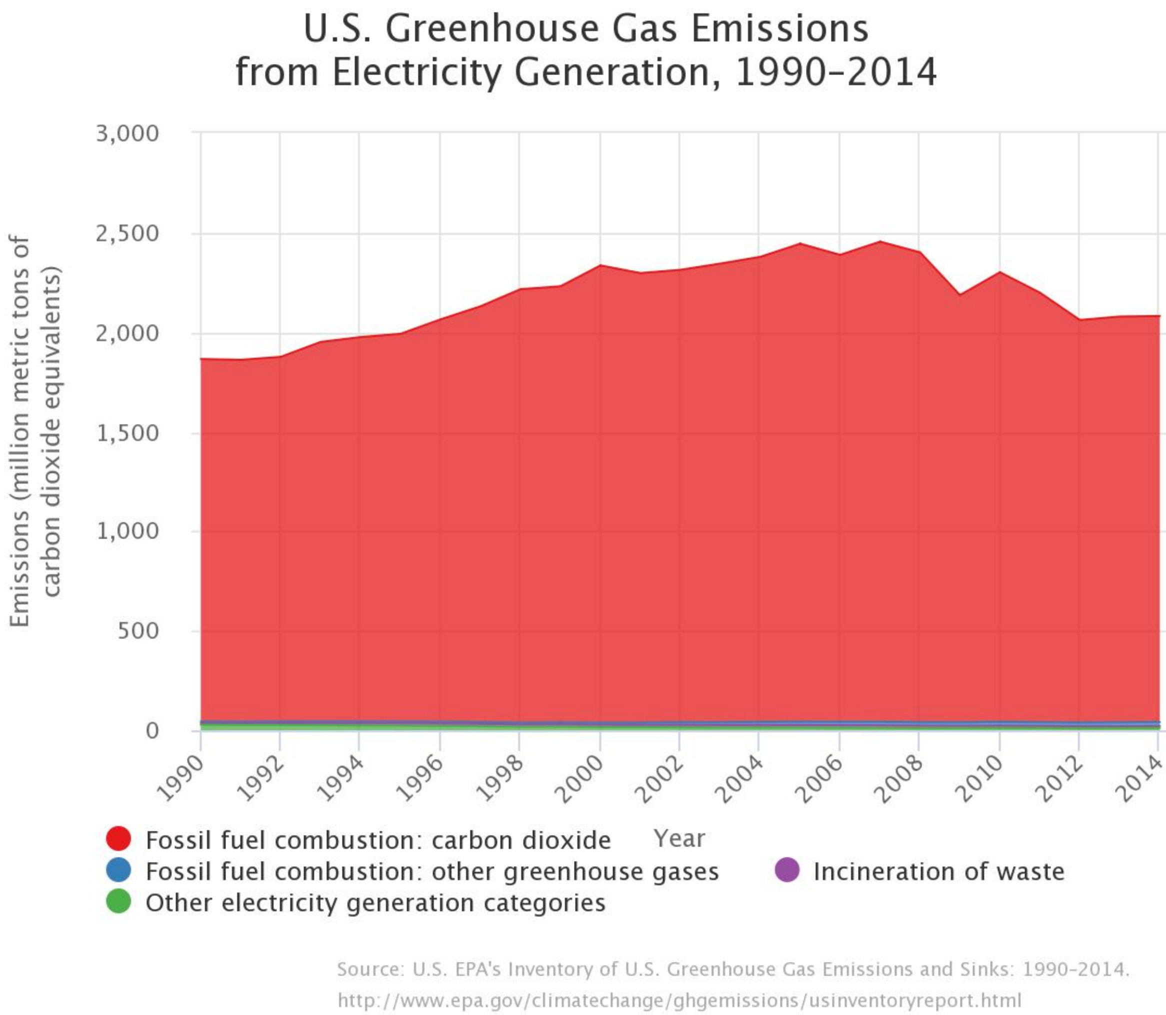


Figure 6: GHG Emissions From the U.S. Electricity Generation Sector From 1990 to 2014 (EPA 2016d)

Green roofs and solar energy, as discussed further in Sections 1.1.5 and 1.1.6 respectively, have both become increasingly popular in recent years as viable solutions with respect to GHG emissions. Solar energy, as previously stated in Section 1.1.3, is a form of renewable energy and can therefore be used as a cleaner alternative to fossil fuel energy, reducing the need for fossil fuels, while solar panels emit no “tailpipe” GHG emissions during use and, on a life-cycle basis, have significantly lower GHG emission rates than fossil fuels, resulting in a net reduction in GHG emissions as fossil fuel energy is gradually replaced with solar energy for the same electricity demand levels. Green roofs, meanwhile, can be used to minimize the transfer of heat through the roof of a building and thus reduce the need for electricity for heating, ventilating, and/or air conditioning (i.e. HVAC), while the presence of plants on green roofs and other rooftop gardens also allows them to reduce GHG emissions more directly via carbon sequestration. Lastly, the integration of solar panels and green roofing in a GRIPV system would allow it to combine the emission-reducing impacts of both options, thus further reducing GHG emissions. Therefore, this study will also look into the potential of all three options to reduce GHG emissions on a long-term basis, particularly as various possible policy scenarios are implemented to maximize their future market penetration levels.

1.1.5 Green Roofs

Green roofs, a.k.a. "vegetated roofs" or "eco-roofs", are specially designed systems installed on rooftops for growing and supporting vegetation on the rooftop, including roof layers placed underneath the vegetation itself to provide drainage and waterproofing, protect the roof underneath from damage from roots, and serve other functions as necessary (Lazzarin et al. 2005; EPA 2008; GSA 2011), as shown in Figure 9. Although green roofs in the literal sense (e.g. Scandinavian sod houses) have existed for thousands of years throughout the world in one form or another, green roofs as a form of green infrastructure were first developed in Germany in the 1970s, and the modern green roof industry has grown rapidly since the 1980s, especially in Europe (Breuning 2016a; Von Fleck 2016). When properly designed, green roof systems allow rooftops to effectively mimic natural landscapes and thus negate, or at least significantly offset, the harmful environmental impacts of urban development (urban runoff, the UHI effect, etc.) as well as the subsequent environmental, societal, and economic effects of these impacts, while also potentially having additional benefits for building owners and/or for the general public (EPA 2008). The most commonly cited and studied environmental benefits of installing green roofs include their ability to significantly reduce urban runoff by more effectively absorbing precipitation and dissipating rainwater and snowmelt into the atmosphere via evapotranspiration, their potential to mitigate the UHI effect by absorbing less heat than conventional roofs and by using evapotranspiration to reduce and stabilize atmospheric temperatures, and their potential to reduce GHG emissions via carbon sequestration and the reduction of energy demand for HVAC purposes. All of these benefits will be explored in more detail in this study, but other general environmental benefits of green roofs beyond the scope of this study may also be possible (GSA 2011; EPA 2008; Garrison et al. 2012), including:

- *Reduced year-round water demand* for the building in question, due to the mitigation of stormwater runoff and the UHI effect as discussed previously, as well as savings on irrigation during runoff events,
- *Increased biodiversity* through the introduction of a new habitat for plants (and possibly animals) in urban areas,
- *Potential increases in urban agriculture* by using green roofs to grow edible plants and/or herbs when possible,
- *Reduced noise pollution* for the building in question, as green roofs are generally better than conventional roofs for absorbing sound, and

- *Improved air quality* in addition to the reduction of GHG emissions, including direct improvements due to the ability of plants to absorb various air pollutants (CO, smog-forming compounds, particulate matter, etc.) as well as indirect improvements as reduced energy demand results in reduced air pollutant emissions from electricity consumption.

Social and economic benefits of the use of green roofs may also be possible, including the following general benefits (GSA 2011; Clark et al. 2008):

- *Longer roof lifetimes*, as green roofs typically last 20+ years longer than conventional roofs by protecting the roof membrane from harmful UV radiation,
- *Greater long-term cost-effectiveness*, especially if savings in HVAC and wastewater costs are taken into account, if local and/or federal incentives are available, and/or if additional revenue can be generated from the recreational and/or agricultural use of the green roof itself,
- *Aesthetic improvements*, as green roofs are generally considered to be more aesthetically attractive compared to conventional roofs,
- *Increased availability of employment opportunities* for both skilled and unskilled workers on a long-term basis, including engineers and maintenance workers, and
- *Potential to increase the real estate market value* of buildings with green roofs relative to those with conventional roofs.

There are, however, some key challenges and possible disadvantages associated with green roofs, especially when green roofs are applied to pre-existing buildings that were originally designed and built with conventional roofs. In general, the main disadvantages and obstacles of installing green roofs are:

- Their *high initial installation costs*, which can range from $10-$25 per square foot (EPA 2008) as opposed to $4-$6 per square foot for conventional roofs (AMS 2016),
- Additional *designing/installation challenges* associated with installing green roofs (particularly on pre-existing buildings originally designed to support a conventional roof), including potential for roof failures due to heavier loads (Jones 2007) and/or poor design specifications (Breuning 2011),
- *Specialized maintenance/repair requirements* for green roofs, including (but not limited to) initial plant establishment, leak detection and management, protection against root penetration, and prevention/management of media biodegradation (GSA 2011), and
- The current *lack of experience with green roof construction/management* among most contractors and roofing installers today, which can lead to budget overruns, construction delays, chronic green roof performance problems, and even outright failure of the green roof system (Breuning 2011; GSA 2011).

In addition to the more general benefits and challenges of green roofs, there are also various specific advantages and disadvantages for each of the three main types of green roofs (extensive, semi-intensive, and intensive) that must also be noted. Conceptual visualizations of these specific types of green roofs are presented in Figure 9, and the specific advantages and disadvantages of each type are summarized in Table 1. This remainder of study will focus more specifically on extensive green roofs, which are the most common green roof type currently being implemented in the U.S. Extensive green roofs can also be divided into "single-course" and "multi-course" extensive green roofs, the main differences being that multi-course extensive green roofs are usually thicker, can (and often do) feature a discrete drainage layer, and can support greater varieties of plants if irrigation and other support systems are available (GSA 2011). However, these differences in design between single-course and multi-course extensive green roofs are beyond the scope of this study, and since regular irrigation is not usually required for extensive green roofs, irrigation water demand for such green roofs can be deemed negligible for purposes of this study.

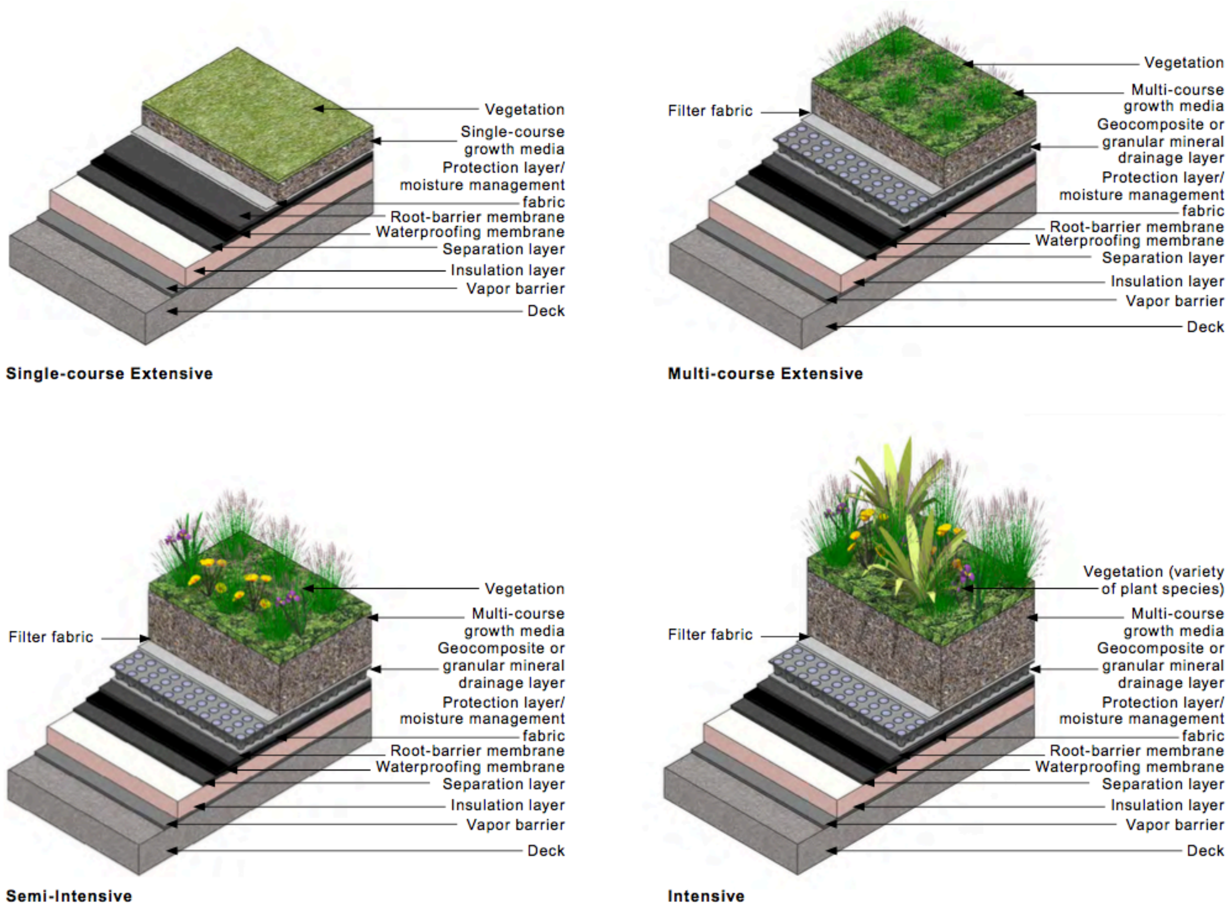


Figure 7: Layers in Different Types of Green Roofs (GSA 2011)

Table 1: Specific Advantages & Disadvantages of Different Green Roof Types

(Breuning 2016b; NPS 2016)

Green Roof Type	*Extensive*	*Semi-Intensive*	*Intensive*
Advantages	• Lightweight • Relatively inexpensive • Relatively simple design • Low maintenance requirements • Best-suited green roof type for retrofitting • Multi-course roofs may allow for more biodiversity	• Can combine benefits and balance out disadvantages of extensive and intensive green roof types to a fairly reasonable extent	• Greatest possible biodiversity • Greatest potential for environmental benefits • Can be designed to accommodate public/private agricultural and recreational use
Disadvantages	• Environmental benefits may be more limited than other green roof types • Less possible biodiversity than other green roof types • Often not accessible for recreational use • Not typically feasible for agricultural use	• Possible benefits are relatively limited compared to purely extensive or purely intensive green roofs	• High maintenance requirements • More expensive than other types • Typically heavier than other green roof types • Generally more complex design requirements • Not usually well-suited for retrofitting

1.1.6 Solar Energy & BIPV Roofing

Solar energy, as the name suggests, is the usable energy from the sun for generating heat and/or electricity, the latter of which is more specifically referred to as solar photovoltaic (PV) energy. The photovoltaic effect, which Antoine Edmund Becquerel first discovered in 1839, is a phenomenon in which certain materials (e.g. silicon) can produce electricity when exposed to light; this effect is the main driving force in solar PV energy production, in which specially designed solar cells (usually as part of an array of solar panels) are directly exposed to sunlight in order to generate usable electricity. The first practically usable solar cells, however, were first invented at Bell Laboratory in 1954, and the market penetration of the solar power industry was still very limited at the time due to high costs and low power-generation efficiencies until the 1970s, when growing environmental concerns and increasing energy and oil prices led to a growing interest in alternative energy sources and the gradual development of cheaper, more efficient, and more reliable solar cells and modules in later years, including the development of solar cells made from different materials in addition to the more traditional silicon solar modules (Jones and Bouamane 2012). Figure 8 shows that, as of 2016, modern solar energy research covers a wide variety of solar cell technologies and materials, with research cell efficiencies reaching as high as 46%.

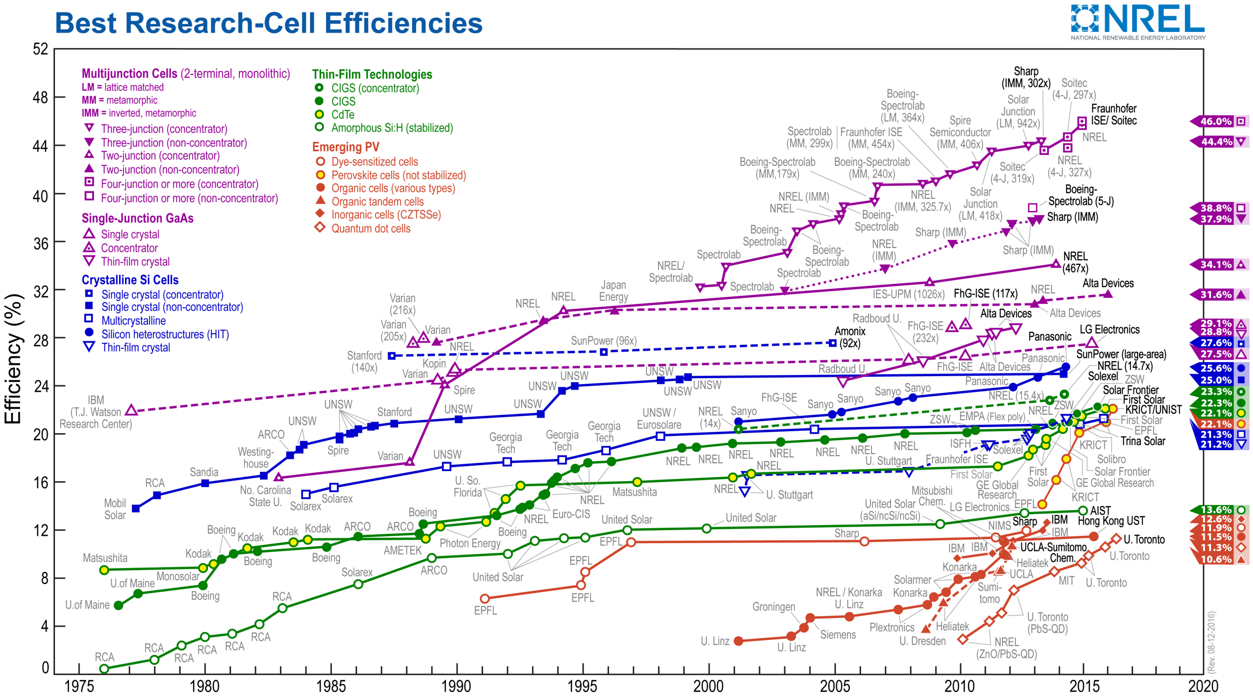


Figure 8: Solar Cell Efficiency Research Progress From 1975 to 2016 (NREL 2016a)

It must be noted, however, that the efficiency levels in Figure 8 are all based on laboratory tests under idealized conditions, and that actual efficiencies of commercially available solar PV modules are therefore likely to be significantly less than their corresponding research cell efficiencies. For example, in 2010, mono- and multi-crystalline silicon PV cells (without concentrators) had optimal research cell efficiencies of 24.92% and 19.69%, respectively, but the average efficiency of commercial c-Si PV modules was 14% for both PV cell types (DOE 2011). The model to be developed in this study will account for this discrepancy as further discussed in Section 4.1.

Solar PV technologies are currently available for many real-world applications, from small-scale charging applications (e.g. solar-charged calculators and household appliances) to larger-scale contributions to local power grids. However, since the main focus of this study is on the use of different alternative roofing options for buildings, the remainder of this study will focus primarily on the use of roof-mounted solar panels to supply renewable energy to the building(s) in question. This study will also investigate the potential of Building-Integrated Photovoltaic (BIPV) solar technology to eventually replace these standard solar panels with solar roof shingles and other such materials, which are designed to effectively replace conventional roofing materials as opposed to mounting a standard array of solar panels onto a pre-existing roof. As such, the potential advantages of roof-mounted solar panels and BIPV solar roof shingles as alternative roofing options include the following:

- *No Fuel Requirements or Emissions During Use:* Unlike conventional energy sources, which derive energy from the combustion of certain fuels (fossil fuels, biomass, etc.) and emit pollutants during the combustion process, solar PV systems do not require any "fuel" inputs other than the energy collected directly from the sun and converted into usable electricity. As a result, solar panels do not emit any pollutants during use, and can therefore potentially reduce emissions of CO_2, SO_2, NO_X, and other air pollutants when used in place of conventional energy sources (Zhai et al. 2012).
- *Scalability & Functionality:* Unlike thermal generators or wind turbines, which tend to lose efficiency at smaller scales of application, solar cells are well-suited for distributed energy generation at any scale, allowing for the development of newer solar PV technologies for a wide range of different applications (Jean et al. 2015). This high level of functionality and technological maturity has helped to

pave the way for BIPV systems as the next major evolution in solar PV technology, as solar roof shingles and other specialized solar PV technologies are being designed to more seamlessly replace conventional building materials and thereby offset or even eliminate many of the current disadvantages of standard roof-mounted solar panels.

- *Potential for Enhanced Shading & UHI Reduction:* Solar PV technologies are best known for their use of solar energy as a renewable energy resource, but recent studies have also shown that they can be used to help offset the UHI effect. These findings may seem counterintuitive at first, particularly because solar PV cells are specifically designed to absorb the sun's energy instead of reflecting it, and are therefore typically designed with lower degrees of reflectivity than the conventional roofs and green roofs previously described (Spaven Consulting 2011). However, solar PV cells are also designed to convert the absorbed solar energy into usable electricity, meaning that the net amount of heat that they release is ultimately less than the amount of energy that they absorb, allowing them to offset or even eliminate whatever adverse UHI effect might otherwise result from their low reflectivity levels. For example, one research study (Golden et al. 2007) found that the use of a PV-modified canopy could reduce pavement surface temperatures by 0.6^{0}F on average compared to a conventional canopy, while another study (Wang et al. 2006) found that the use of BIPV solar roofing in a building could potentially reduce heat fluxes in and out of the building in this manner and/or use the solar electricity that they generate to offset the building's

HVAC electrical loads, especially if a sufficient "air gap" (preferably with ventilation) can be provided between the solar roofing and the main roof.

On the other hand, although the solar energy industry continues to advance considerably and has a generally optimistic future in many respects, current solar PV and solar roofing technologies still have their share of disadvantages that must be addressed before they can be more widely implemented. These current disadvantages, many of which can potentially be addressed in future BIPV research, typically include the following:

- *Dependence on Sunlight & Other External Factors:* Solar PV energy is not "produced" in the literal sense, but must instead be collected directly from the sun and then converted into usable electricity. Therefore, the successful application of any solar PV system must take into account all available locations and angles at which the solar array can be placed in order to expose it to as much sunlight as possible and thus maximize the power output of the system. Furthermore, even a perfectly placed solar PV system may lose efficiency depending on a number of external factors that may be beyond the designer's control, such as temperature (Radziemska 2003) and adverse weather conditions (e.g. cloudiness).
- *High Costs vs. Other Renewable Energy Sources:* The U.S. Energy Information Administration (EIA) estimated a total Levelized Cost of Electricity (LCOE) of \$84.70/MWh (in 2015 U.S. dollars) for solar PV power, excluding capacity weighting and tax credits. The corresponding LCOE estimates for onshore wind power, hydroelectric power, and geothermal power were \$64.50/MWh, \$67.80/MWh, and \$45.00/MWh, respectively (EIA 2016b).

- *Complexity of Higher-Efficiency Systems:* Silicon wafer-based technologies (e.g. mono- and poly-crystalline silicon) are widely considered to be the "standard" system among solar PV systems in both laboratory research and industrial practice, having historically been the dominant form of technology in the solar PV market with global market shares of 93% as of 2015 (Fraunhofer ISE 2016). In comparison, based on the laboratory efficiencies previously cited in Figure 8, higher-efficiency technologies generally consist of concentrator-enhanced silicon cell systems, multi-junction solar cells, and gallium arsenide solar cells, all of which are more expensive and require more complex manufacturing than traditional silicon-based technologies. On the other hand, relatively simpler and cheaper technologies (e.g. thin-film cells) have historically been less efficient than traditional silicon cells.
- *Additional Loads:* Traditional solar roofing applications consist of simply mounting an array of solar panels onto a pre-existing roof. Consequently, these solar panels will place additional loading on the roof that must be accounted for prior to application, as failure to do so may lead to roof failures and other problems with the system. The mounting equipment of a standard roof-mounted solar PV array typically weighs about 3-4 pounds per square foot of solar panel area (Diehl 2015), among other roof loads that must also be considered.

Despite the current impacts of these disadvantages on the solar roofing industry and the solar PV market in general, current BIPV research shows that future technologies may offset or even eliminate these disadvantages in the near future. For example, as previously shown in

Figure 8, the efficiencies of thin-film technologies and other emerging PV technologies are now becoming more comparable with traditional silicon wafer-based technology in terms of efficiency, allowing for the potential of BIPV technologies (e.g. solar roof shingles) to become cheaper and easier to implement in the future without sacrificing energy efficiency or power output. The costs of other renewable energy resources and the impacts of external factors on solar panel efficiency are both beyond the scope of this research, and since crystalline silicon technologies have historically been the dominant solar PV technology, the remainder of this study will focus more specifically on the use of crystalline silicon for solar PV power, while also accounting for the potential of future BIPV research to increase solar cell efficiency and/or reduce solar panel loads on rooftops to allow for easier installation.

1.1.7 GRIPV Roofing Systems

Green roofs and BIPV roofing are both steadily gaining popularity as alternatives to conventional roof designs, but now a new alternative has begun to emerge that effectively combines green roofs and roof-mounted solar panels into a single integrated system. This new alternative, now commonly referred to as PV-Green roofs or Green Roof Integrated Photovoltaic (GRIPV) systems, is currently not as widespread in today's alternative roofing market as green roofs and solar panels are separately, especially in North America, whereas green roofs in Germany were being retrofitted with solar PV panels as early as 1999 (Köhler et al. 2002). Moreover, available GRIPV literature and data is also very limited, and as of 2016, the available literature lacks sufficient replication plots, limiting the inferences that can be derived from the literature with respect to GRIPV systems in general (Schindler et al. 2016). Nevertheless, the available literature has consistently shown that GRIPV systems have considerable potential as an alternative roofing option, particularly as a potential improvement over roof-mounted solar panels alone, and GRIPV applications have recently begun to emerge in North America as well; the first fully-integrated GRIPV system in North America was introduced in 2011 in Philadelphia, P.A., after which it first became commercially available in 2012 and the first GRIPV system in the U.S. was installed later that year in New York City (Breuning 2012; Breuning 2013).

In current practice, a typical GRIPV system design (Figure 9) essentially consists of an array of solar PV panels mounted above a green roof, resulting in the system as a whole having many of the individual advantages of each separate component, including (but not limited to) the higher rainfall retention of a green roof and the electricity generation capabilities of a solar PV system. However, in addition to these separate advantages, GRIPV systems can also make use of a number of symbiotic benefits between its green roof and solar PV components. Examples of these symbiotic benefits primarily include, but are not limited to, the following (Perez et al. 2012; Schindler et al. 2016; Lamnatou and Chemisana 2015):

- *Improved Solar PV Energy Efficiency*: Evapotranspiration from the green roof can provide an additional cooling effect for the solar panels and thus reduce the damaging effects of heat on solar panel performance, increasing the efficiency and overall energy production of the solar array.
- *Enhanced Environment for Green Roof Vegetation*: The solar panels can provide shade for the vegetation on the green roof as well as shelter from wind and other adverse weather conditions, which can potentially encourage greater biodiversity

and plant growth on the green roof while also enhancing soil moisture and extending growth periods.

Figure 9: Example of a Typical GRIPV Roof System (Optigreen International AG 2017b)

Due to the limited availability of GRIPV literature and the currently limited number of real-world examples (especially in the U.S.), the disadvantages of GRIPV systems are not yet fully understood in academic research or in industrial practice. Potential disadvantages of GRIPV systems in practice as cited in the available literature include, but may not be limited to, the following (Hui and Chan 2011; Witmer 2010; Lamnatou and Chemisana 2015; Schindler et al. 2016):

- *Heavier Roof Loads:* Current GRIPV roof designs generally consist of an array of solar panels mounted on a green roof as part of a single integrated system. Consequently, such a system will tend to be heavier per unit area than either a green roof or a solar PV array individually, especially since the green roof component of a typical GRIPV system will cover the entire roof area, while the PV modules of this same typical system are mounted above the green roof component and may result in increased wind loads compared to other conventional or alternative roof types.
- *Specialized Design Considerations:* Due to their integrated nature, GRIPV systems must be carefully designed, with a wide range of crucial factors taken into account, in order to optimize the performance of their green roof and solar PV components and to avoid unforeseen complications. The selection of appropriate plant species for the green roof component is especially important in this regard, and the specific requirements for the green roof vegetation may vary depending on environmental conditions, system specifications, and other factors as applicable for each individual GRIPV system. For example, the vegetation of the green roof should consist of plants with canopies shorter than the height of the mounted PV panels, or else the higher plant canopy may result in practical complications with respect to PV panel placement and/or reduced PV energy output due to partial or complete shading of the panels. Likewise, plant species that have less tolerance for shade should not be planted underneath a solar panel

or otherwise within the shaded area of the solar PV array, as doing so may impact their growth and overall condition.

- *Limited Information/Experience*: The research and application of GRIPV systems is still very limited today, especially in the U.S., and most of the available data from the literature has not yet been sufficiently replicated to allow for any clear inference as to the true extent of the potential benefits and/or disadvantages of GRIPV systems, particularly with respect to the potential impacts of their two primary components (a green roof and a solar PV array) on each other, as well as how these impacts may affect the design and performance of a particular GRIPV system. To account for this research gap as needed in this study, appropriate assumptions will be made based on current knowledge regarding green roofs and solar PV systems individually.

The specific impacts of different plant characteristics, environmental conditions, and design specifications on GRIPV performance are beyond the scope of this study. Instead, a constant parameter based on available data from the literature will be used to represent the overall improvement in the energy efficiency of a GRIPV system relative to that of a standard roof-mounted solar PV array, and the overall cooling effect with a GRIPV system will be assumed to be proportional to the individual cooling effects of green roof vegetation and solar PV panels, among other assumptions as necessary. Likewise, the overall roof load per unit of a GRIPV system will be calculated based on the corresponding individual loads of a green roof and a roof-mounted solar PV array.

1.1.8 System Dynamics

Originally developed by Jay W. Forrester (Forrester 1971), System Dynamics (SD) is a computer-aided modeling and simulation methodology used to comprehensively analyze complex social and industrial systems on a long-term basis and to thereby address key problems observed within the system by analyzing the long-term effectiveness and/or feasibility of prescribed solutions for such problems. To do this, the SD methodology primarily uses a *systems thinking* perspective, in which different variables (often including variables across different disciplinary spheres, such as environmental and socio-economic variables) are all modeled simultaneously over a given period of time within the context of the system in order to analyze the complex interdependent relationships between such variables, which are often represented by *feedback loops* that illustrate how changes in one variable may subsequently influence other variables, while delays may also be simulated wherever the cause-and-effect relationship between two directly connected variables does not take effect instantaneously (Andersson and Karlsson 2001). The basic steps of the SD procedure are as follows (Williams and Harris 2005; Binder et al. 2004):

1. *Problem/Hypothesis Identification:* The problem to be addressed is identified, and a hypothesis is proposed as to the possible underlying cause of the problem, so that the SD model can be developed to encompass the relevant aspects of the system with respect to the problem to be solved and the proposed hypothesis.
2. *Parameter Selection:* Variables found to be relevant to the problem are analyzed, with some variables excluded as necessary to avoid overcomplicating the SD model and/or to focus more specifically on certain other variables. Variables not

excluded in this manner are selected as parameters for the model, and are analyzed in more detail in subsequent steps.

3. *Conceptualization:* A causal loop diagram (CLD) is drawn in which positive and negative arrows are used to connect variables with direct cause-and-effect relationships. Arrows with two dashes indicate a delay, meaning that the cause-and-effect relationship between the two connected variables is not instantaneous. Arrows that form a complete closed loop indicate the existence of a feedback loop; feedback loops in which an increase in one variable results in a subsequent additional increase are called *positive/reinforcing feedback loops*, while feedback loops in which an increase in one variable results in a subsequent decrease are called *negative/balancing feedback loops*.
4. *Formulation:* Based on the conceptual relationships from the CLD, a stock-flow diagram (SFD) consisting of stocks, flows, and auxiliary variables is developed in a specially designed computer program (e.g. Vensim PLE Plus) to apply the qualitative feedback relationships of the CLD to a practical quantitative analysis using relevant data, mathematical formulae, and auxiliary factors as applicable. The SFD forms the finalized SD model, which can then be simulated in subsequent modeling steps.
5. *Validation:* Appropriate structural and behavioral tests are applied to the developed SD model in order to ensure that the model is an adequate representation of the modeled system in reality and that it is well suited to analyze the problem and hypothesis from Step 1. Where available, a *reference mode*

consisting of historical data is used to ensure that the simulated behavior of the model is valid, with statistical analyses included as deemed appropriate; if no reference mode is available for this purpose, it must instead be proven that the model's behavior is still reasonably accurate based on all available knowledge and data applying to the model output in reality. Changes must be made as needed if the developed model fails any of these structural or behavioral tests. Once the finalized model passes all of these tests, the model is considered validated and ready for subsequent steps.

6. *Analysis:* The validated model is used to study the problem and hypothesis from Step 1, usually by evaluating the effectiveness and/or feasibility of one or more proposed solutions to the problem. To simulate these proposed solutions, adjustments are made to the corresponding variable(s) in the model before beginning each simulation run. For example, in a model developed to analyze the effects of capital subsidies and feed-in tariffs on the market penetration of solar photovoltaic (PV) systems, one might adjust variables representing the subsidized portion of the cost of the solar PV system and the starting feed-in tariff price, respectively, and then simulate the model to see how such adjustments would affect the total installed capacity of solar PV systems (Hsu 2012).
7. *Final Review:* The results of the simulations in Step 6 are analyzed, and conclusions are drawn with respect to the problem, the proposed hypothesis, and the simulated solutions based on these results. Recommendations are made as appropriate, and any limitations or other difficulties encountered during the

analysis and/or the modeling process are usually discussed along with possible suggestions as to how these limitations/difficulties may be addressed in future research.

A wide range of software programs is available today to model and simulate SD problems, including Vensim (the program used in this study), Powersim, Dynamo Plus, Stella/ithink, and Extend (Andersson and Karlsson 2001). In this paper, the market penetration of green roofs, solar PV/BIPV roofing, and GRIPV roofing systems will be modeled using a non-complementary, multiple-choice version of the Generalized Bass Model, which will be discussed in further detail in Section 1.1.8.1.

1.1.8.1 Generalized Bass Model

Originally formulated by Frank Bass in 1969, the Bass Diffusion Model (BDM) is a mathematical model used to estimate the adoption rate and cumulative adoption of a new product or innovation over time, including adoption by "innovators" who adopt the new product/innovation independently of any previous degrees of adoption, as well as adoption by "imitators" who are motivated to adopt the product/innovation via the word-of-mouth effect after interacting with previous adopters (Bass 1969). The BDM itself consists of the following differential equation:

$$P(t) = \frac{f(t)}{1 - F(t)} = p + qF(t) \tag{1}$$

Where "P(t)" is the probability of adoption at time t, "f(t)" is the adoption rate at time t, "F(t)" is the cumulative adoption at time t, "p" is the coefficient of innovation, and "q" is the coefficient of imitation. Since its development, the BDM has been frequently used to illustrate the long-term market penetration of new technologies, making it an ideal modeling framework for SD market penetration analyses. In a typical SD simulation of the BDM, the coefficient of innovation ("p") is set equal to a specific constant representing the overall effectiveness of advertising for the new product/innovation being considered, while the coefficient of imitation ("q") is more complex and depends on factors such as the rate of interaction between previous adopters and potential adopters, the probability of adoption by an "imitator" after such interactions, and so on (Baran 2010). A typical SFD of the BDM in its most basic form is presented in Figure 10, and more detailed SD formulation for this SFD is summarized in Table 2. As shown visually in Figure 11, the SD simulation results of the BDM in this form generally follow a pattern in which the adoption rate increases until it reaches its maximum value in a certain peak year and then decreases back to zero afterward, resulting in a relatively steady increase in the cumulative adoption until it eventually plateaus once the adoption rate decreases to zero.

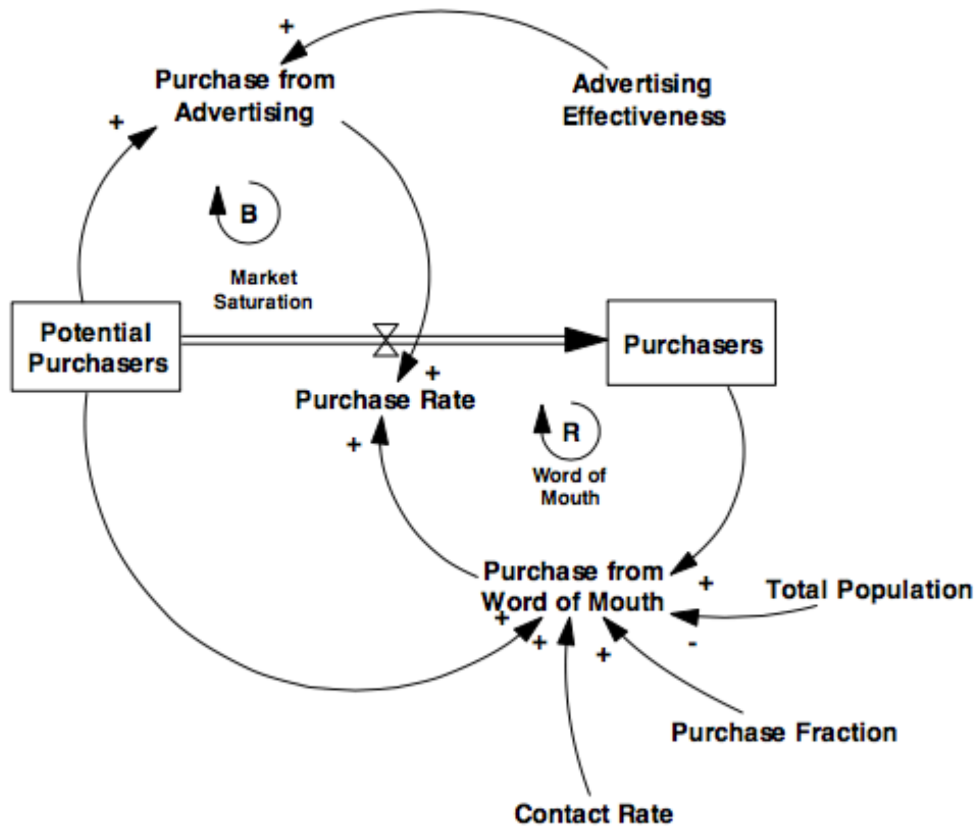


Figure 10: Typical SFD of the Standard BDM (Baran 2010)

Table 2: SD Formulation for the Standard BDM (Baran 2010)

Variable Name	*Potential Purchasers*	*Purchasers*	*Purchase Rate*	*Purchase from Advertising*	*Purchase from Word of Mouth*
Variable Type	Stock	Stock	Flow[a]	Auxiliary	Auxiliary
Units	Units	Units	Units/Yr	Units/Yr	Units/Yr
Formula	$INTEG\begin{pmatrix}-Purchase\ Rate, \\ Initial\ Value\end{pmatrix}$	$INTEG\begin{pmatrix}Purchase\ Rate, \\ Initial\ Value\end{pmatrix}$	$Purchase\ From\ Advertising + Purchase\ From\ Word\ of\ Mouth$	$Advertising\ Effectiveness * Potential\ Purchasers$	$Contact\ Rate * Purchase\ Fraction * Potential\ Purchasers * \left(\frac{Purchasers}{Total\ Population}\right)$
Initial Value	May Vary[b]	May Vary[c]	N/A	N/A	N/A

[a]Flows from "Potential Purchasers" to "Purchasers".
[b]Equal to the total non-purchaser population at the beginning of the initial simulation year that is potentially willing to become purchasers.
[c]Equal to the total purchaser population at the beginning of the initial simulation year.

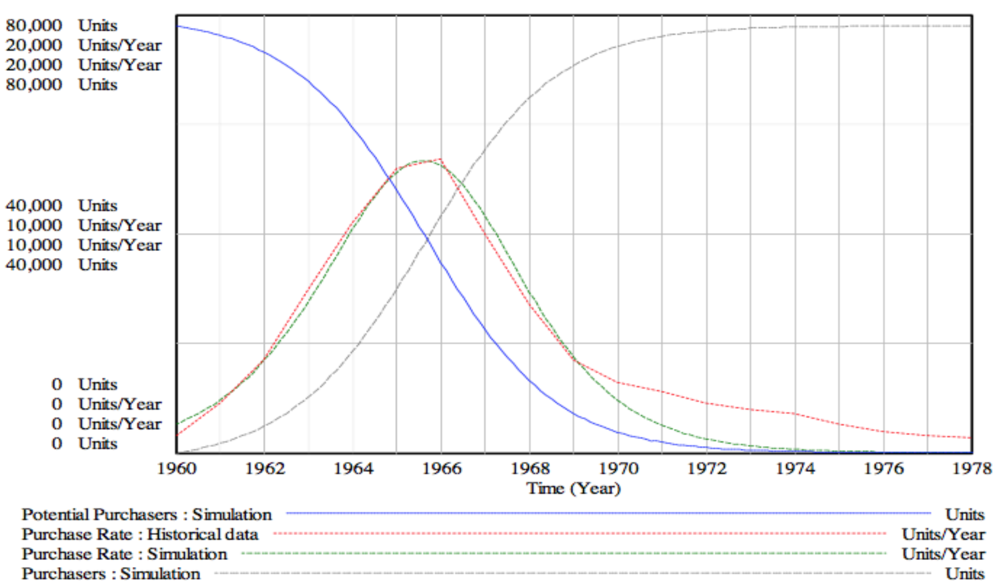


Figure 11: Typical Simulation Result Patterns for the Standard BDM (Baran 2010)

The BDM in its original form has proven to be a surprisingly accurate representation of the market penetration of new technologies for over 30 years, especially for brand new technologies for which no non-conventional competing alternatives are available. However, various extensions of the BDM have also been discussed in relevant literature. Most notably, Bass et al. (1994) formulated a modified version of the BDM called the Generalized Bass Model (GBM), as shown in Equation 2 below.

$$P(t) = \frac{f(t)}{1 - F(t)} = [p + qF(t)][x(t)] \qquad (2)$$

Where "x(t)" is a function of the market conditions at time t, including price changes and other relevant market variables. It must be noted that the formula for the GBM (Equation 2) is identical to that of the BDM (Equation 1) except for the inclusion of "x(t)" as an influencing variable. Therefore, a similar concept may be used in the SD model developed in this study to account for economic influences and other external factors on the diffusion of green roofs and/or solar PV roofing as viable alternatives to conventional roofs. Additional extensions to the BDM will be discussed in the corresponding literature review in Section 2.1.4.

1.1.9 Study Area

The specific regional area that this study focuses on is the U.S. city of Orlando, F.L. A current map image of Orlando is shown in Figure 12a to illustrate the boundaries of the study area, while a corresponding satellite image of Orlando is shown in Figure 12b. The grey and white areas in the satellite image, which indicate areas with significant levels of urbanization, cover a vast majority of the region within the boundaries shown in Figure 12a, making Orlando a good example of an urban area for purposes of this study.

(a) (b)

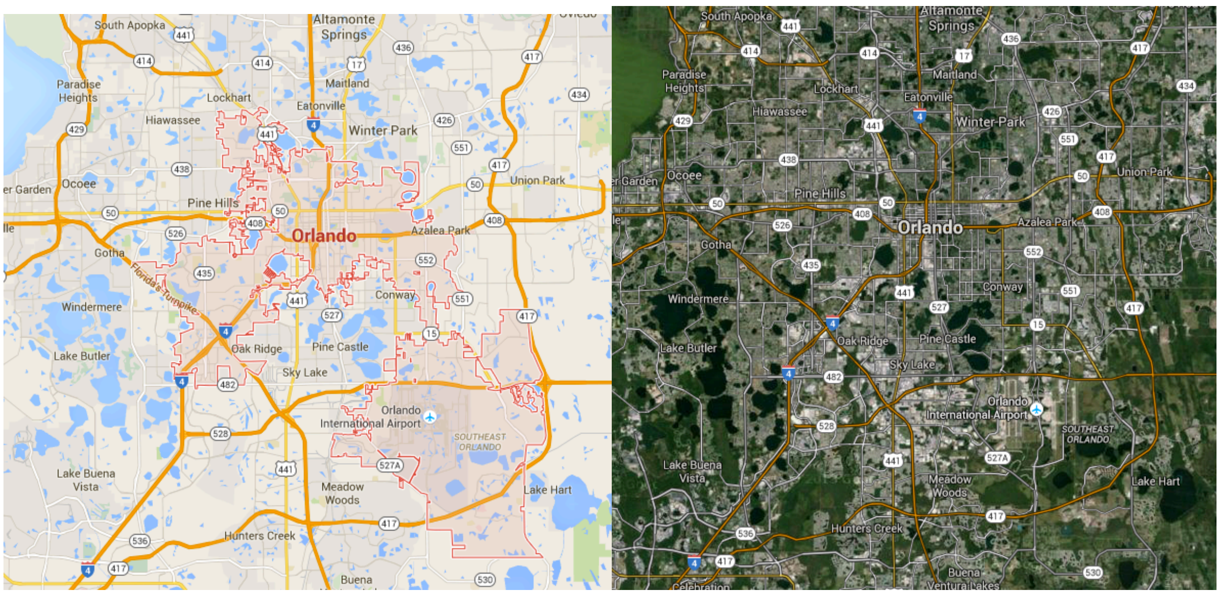


Figure 12: Map & Satellite Image of Orlando, Florida (Google 2016)

(a) Illustration of Boundaries (b) Satellite Image

The next four sub-sections will summarize and discuss the relevant data for the city of Orlando with respect to the parameters to be analyzed in this study:

- Runoff (Section 1.1.9.1),
- Temperature (Section 1.1.9.2),
- Energy demand & savings goals (Section 1.1.9.3), and
- GHG emissions & savings goals (Section 1.1.9.4).

1.1.9.1 Runoff From Study Area

Total annual precipitation data is readily available from the Florida Climate Center (FSU 2016) for a variety of locations in the state of Florida. For purposes of this study, the data for the city of Orlando (specifically the Orlando International Airport) has been collected from the year 1985 to the year 2013, which is the historical time period to be used for validation purposes as discussed further in Section 4.2.2. The total annual precipitation in Orlando for each year in the selected validation period is presented in Figure 13, along with the long-term average annual precipitation from 1985 to 2013. Annual precipitation data is also available for 2014, but this 2014 data will not be used for the validation period due to insufficient historical data for other required variables in the year 2014, though this data will still be considered for policy analysis purposes. Future predictions for annual precipitation will be based on a linear regression of all available historical precipitation data.

Annual Storm Runoff Coefficients (ASRCs) have been estimated in past literature for pervious and impervious surfaces specifically for the Orlando, Florida area (Pandit and Gopalakrishnan 1996), and these ASRCs will be used to calculate the total annual runoff from conventional roofs and undeveloped land, respectively; annual runoff from green and GRIPV roofs will instead be calculated based on annual green roof rainfall retention rates (Figure A1), while solar panels are assumed to be impervious surfaces for annual runoff calculation purposes. A full summary of the runoff-related study area characteristics to be used in this study is provided in Table 3.

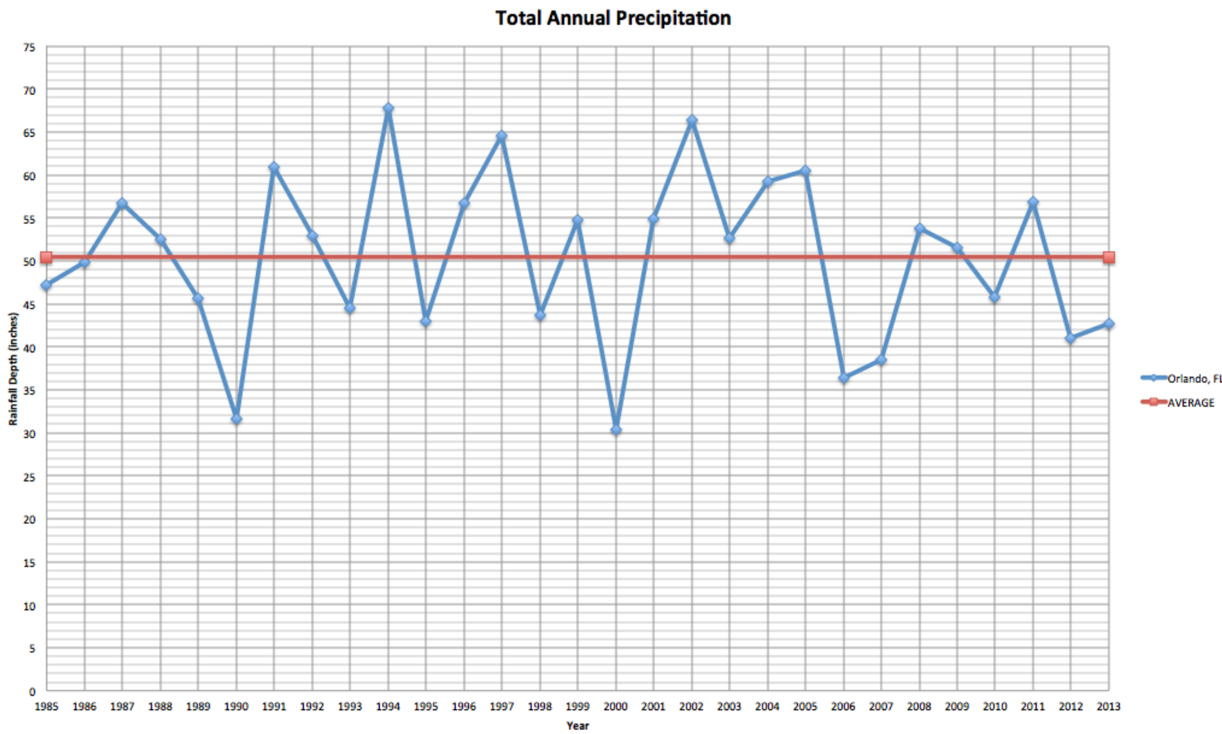


Figure 13: Annual & Long-Term Average Precipitation in Orlando, F.L. from 1985 to 2013

(FSU 2016)

Table 3: Study Area Characteristics Relevant to Urban Runoff

Characteristic	*Average Annual Precipitation*	*Average Impervious ASRC*	*Average Pervious ASRC*	*Wastewater Costs*
Value	50.46 inches	0.72	0.095	$3.68 per 1,000 gallons as of 2016
Source	(FSU 2016)	(Pandit and Gopalakrishnan 1996)	(Pandit and Gopalakrishnan 1996)	(OCU 2016)
Comments	Based on long-term average of precipitation data from 1985 to 2013.	Estimated ASRC value of 100% impervious surfaces in Orlando, Florida.	Estimated ASRC value of 100% pervious surfaces in Orlando, Florida.	Wastewater rates in Orange County are the same for residential and commercial use.

1.1.9.2 Temperature In Study Area

Average annual temperature data is readily available from the Florida Climate Center (FSU 2016) for a variety of locations in the state of Florida. Like with precipitation, the station chosen to represent temperature data from the city of Orlando corresponds more specifically to the Orlando International Airport. However, in order to properly measure the urban heat island effect, a non-urban station must also be selected for comparison; the closest non-urban station to the Orlando International Airport station is the “Clermont 9 S” station. Annual mean temperature data has been collected for both stations from the year 1985 to the year 2013, which is the historical time period to be used for validation purposes as discussed further in Section 4.2.2. The mean annual temperature data for both of these stations and the corresponding historical temperature anomalies between them within this time period have been plotted as shown in Figures 14 and 15 respectively, along with their respective long-term average values from 1985 to 2013. Future predictions for mean annual rural temperature in Orlando (the "Clermont 9 S" station") will be based on a linear regression of available historical temperature data.

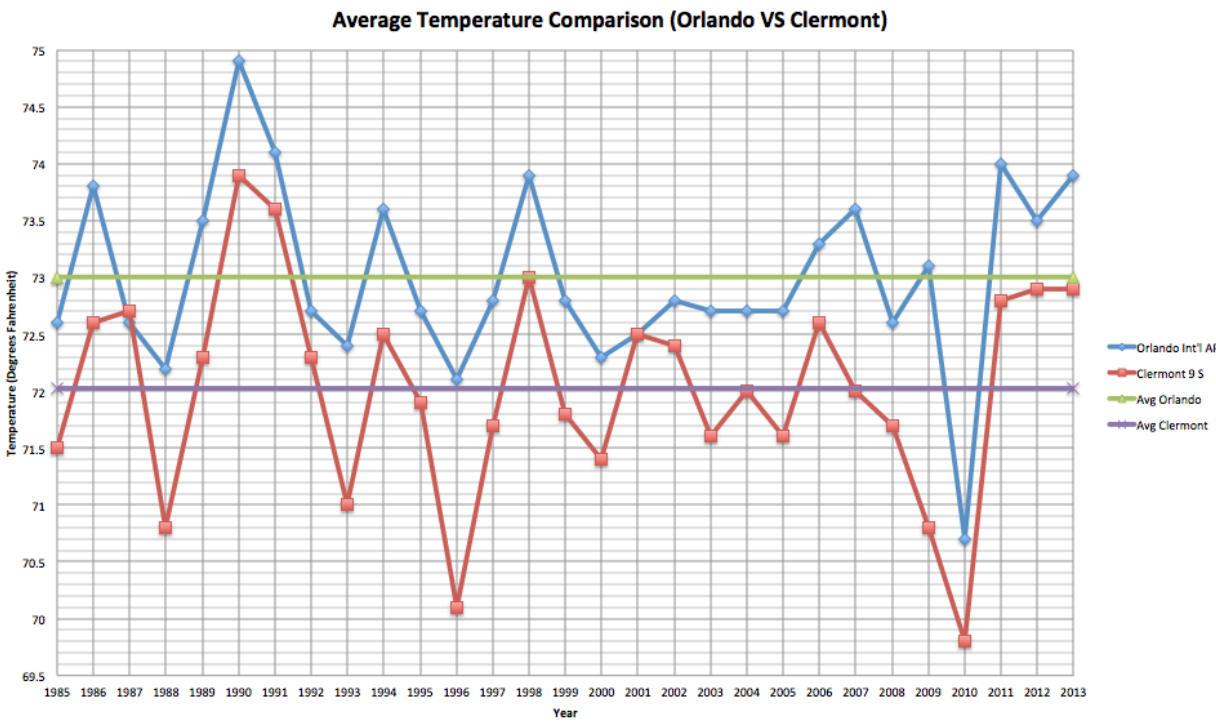


Figure 14: Average Mean Annual Temperatures for Orlando & Clermont from 1985 to 2013 (FSU 2016)

This data indicates that, on average, temperatures in the urban Orlando station were approximately 1^0F hotter than in the non-urban Clermont station between 1985 and 2013. While this difference in temperature is not as significant as those of other UHIs, for which temperature differences can range from 1.8^0F to 5.4^0F as previously explained (EPA 2008), it is still significant enough to warrant further analysis for the UHI effect in Orlando. Furthermore,

Figure 15 shows that this temperature difference reached as high as 2.3^{0}F in 2009, indicating that the UHI effect in Orlando on a short-term basis may be more serious in certain years than the long-term average data may indicate, depending on a variety of factors that cannot be fully accounted for in this study alone.

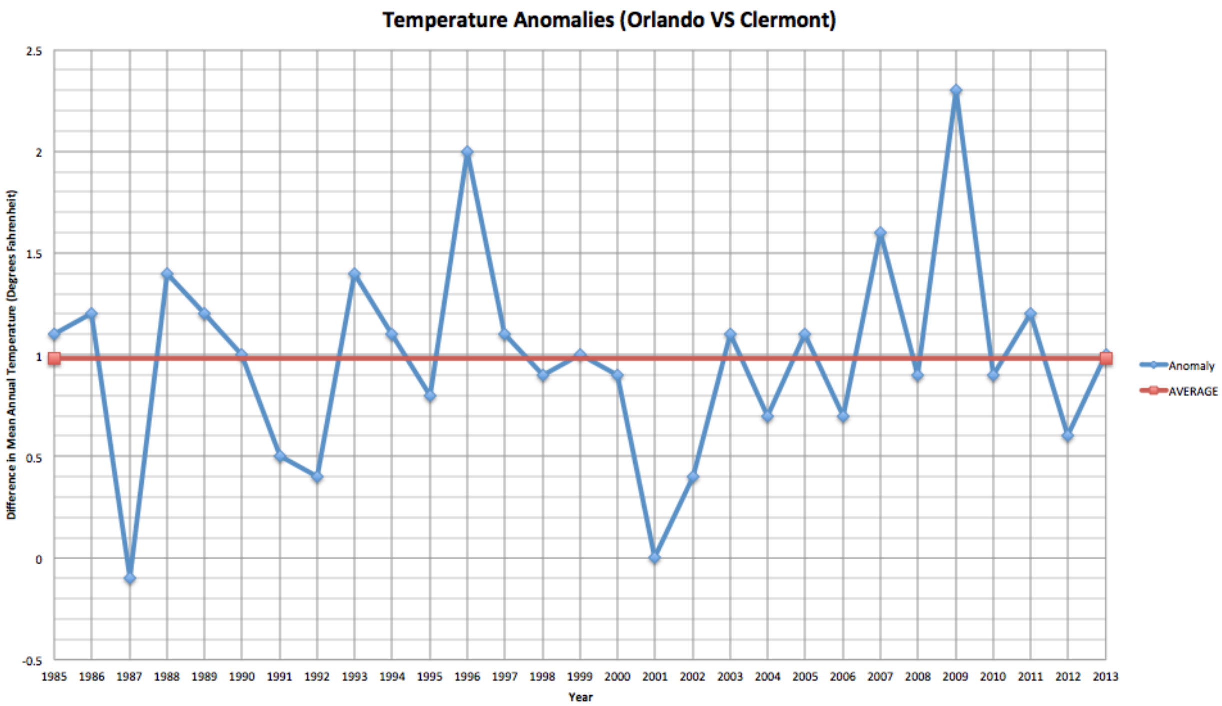


Figure 15: Mean Temperature Anomaly From 1985 to 2013 (FSU 2016)

The horizontal solar radiation, or *horizontal insolation*, in the Orlando area is required in order to determine how much solar energy the city of Orlando receives regularly, which will be necessary to calculate the temperature anomaly between an urbanized Orlando and a hypothetical non-urban landscape in the Orlando area. The calculations and additional data used for this purpose will be discussed further in Section 4.1.4. Based on the most recent available monthly insolation data for the city of Orlando (Tukiainen 2005), the average annual insolation for the city of Orlando is approximately 5.1 kWh per m^2 per day.

A full summary of study area characteristics as they apply to temperature and the UHI effect is provided in Table 4.

Table 4: Study Area Characteristics Relevant to Temperature & the UHI Effect

Characteristic	*Average UHI Temperature Anomaly*	*Peak UHI Temperature Anomaly*	*Average Annual Horizontal Insolation*
Value	$+1^0$F	$+2.3^0$F	5.1 kWh/m^2-day
Source	(FSU 2016)	(FSU 2016)	(Tukiainen 2005)
Comments	Temperature difference between long-term averages of Orlando (urban) and Clermont (non-urban) data from 1985 to 2013.	Maximum of temperature differences between Orlando (urban) and Clermont (non-urban) mean annual temperature data from 1985 to 2013. This peak anomaly was observed in 2009.	This was the most recent data available for the city of Orlando, based on monthly data from 1983 to 2005.

1.1.9.3 Energy Demand In Study Area

Due to lack of sufficient area-specific time series data to plot a reference mode regarding energy consumption in the city of Orlando, this study will instead focus on the current and potential progress in achieving the energy demand reduction targets established for the city of Orlando (Green Works Orlando 2016) through the implementation of green roofs, solar panels, and GRIPV systems, particularly with respect to the ultimate energy savings goal established for the year 2040. These targets are briefly summarized in Table 5, and other relevant characteristics for the study area are summarized in Table 6. The latter includes the horizontal insolation as previously discussed in Section 1.1.9.2, as well as the average annual number of "sun-hours" during which solar energy can be generated, both of which are required to determine how much solar energy the city of Orlando receives regularly and thus calculate the potential annual power output of a solar array per unit area.

Table 5: Energy Demand Reduction Targets & Baseline Information for the City of Orlando

Characteristic	*Baseline Energy Demand Per Capita*	*2018 Energy Demand Target*	*2040 Energy Demand Goal*
Value	12,003 kWh/capita	11,403 kWh/capita	9,602 kWh/capita
Source	(Green Works Orlando 2016)	(Green Works Orlando 2016)	(Green Works Orlando 2016)
Comments	Energy use per capita in the city of Orlando in 2010.	5% reduction from baseline (2010) energy consumption.	20% reduction from baseline (2010) energy consumption.

Table 6: Study Area Characteristics Relevant to Energy Demand

Characteristic	*Average Annual Horizontal Insolation*	*Total Annual Sun Hours*
Value	5.1 kWh/m^2-day	1,821.35 hours
Source	(Tukiainen 2005)	(Solar Direct 2016)
Comments	Based on monthly data over a 22-year period (1983-2005). This was the most recent data available for the city of Orlando.	Based on the average daily year-round sun hours for the closest city to Orlando (Belle Island, FL).

1.1.9.4 GHG Emissions in Study Area

Due to lack of sufficient area-specific time series data to plot a reference mode regarding GHG emissions in the city of Orlando, this study will instead focus on the progress made by the alternative roofing industry in achieving the GHG emission reduction targets established for the city of Orlando (Green Works Orlando 2016), particularly with respect to the ultimate goal established for the year 2040. These targets are briefly summarized in Table 7, along with the EPA's estimated GHG emission factors for electricity generation (EPA 2015), which will be used to calculate the GHG emission savings from reducing and/or offsetting energy demand from the main power grid.

Table 7: Study Area Characteristics Relevant to GHG Emissions

Characteristic	*Baseline GHG Emissions*	*2018 GHG Emission Target*	*2040 GHG Emission Goal*	*GHG Emission Factor*
Value	5,803,851 tons of CO_2	4,352,888 tons of CO_2	580,385 tons of CO_2	1,125.35 lb CO_2/MWh
Source	(Green Works Orlando 2016)	(Green Works Orlando 2016)	(Green Works Orlando 2016)	(EPA 2015)
Comments	GHG emissions in the city of Orlando in 2007.	25% reduction from baseline (2007) GHG emissions.	90% reduction from baseline (2007) GHG emissions.	Regional electricity GHG emission factor for the state of Florida (FRCC region).

1.2 Problem Statement

Although green roofs are considerably widespread today in other parts of the world, particularly in Europe, the U.S. market for green roofs is still growing at a very slow rate, with only a marginal increase in green roof market penetration in the U.S. over the last few years, prior to which green roofs in the U.S. were virtually nonexistent (Von Fleck 2016). On the other hand, solar PV technology has demonstrated considerable progress as a renewable energy resource and is the fastest-growing energy technology in the world today, but despite this progress and the significant potential of BIPV technology to become even more user-friendly and cost-effective in the near future, the market penetration of solar PV energy is still very limited, with solar PV power accounting for only 0.87% of the total worldwide electricity demand in 2013 (Jean et al. 2015). Furthermore, despite showing significant promise in recent literature as a viable form of green infrastructure, GRIPV roofs are virtually nonexistent in the U.S. today, and available literature and data on such systems is still very limited, making it difficult for today's roof buyers and policy-makers to fully understand the potential benefits and/or challenges with respect to GRIPV systems and thus further hindering the development and implementation of GRIPV roofing in practice. These are all examples of *policy resistance*, or "the tendency for well-intentioned interventions to be defeated by the response of the system to the intervention itself" (Sterman 2002). As a result, despite whatever short-term benefits they may have in any particular case, these interventions fail to provide an effective long-term solution to the problems that they were intended to solve, typically due to some unforeseen response to the solution in question on part of the system as a whole, and can sometimes make the problem even worse in the long run.

In the U.S. green roof market, this policy resistance is believed to stem primarily from the main disadvantages and challenges currently associated with various types of alternative roofing systems, as previously discussed in Sections 1.1.5 through 1.1.7. With respect to green roofs, for example, these can include the relatively high installation costs of green roofs and their potential for specialized installation and/or maintenance requirements, as well as the relative inexperience of roofing contractors in the U.S. with green roof installation. In particular, retrofitting green roofs onto pre-existing buildings that were not originally designed to support green roofs (which tend to be heavier than conventional roofs) may lead to roof failures and complications in the construction process, making green roof market penetration even more difficult in practice.

In the U.S. solar PV market, this policy resistance is likewise believed to stem primarily from the practical limitations and disadvantages of current forms of solar PV technology, particularly with respect to the crystalline silicon solar panels that currently dominate the global solar PV market. Although some of these limitations (solar array placement, impacts of temperature/weather on module efficiency, etc.) are beyond the scope of this study, other limitations include the current need for more complex solar PV systems to meet higher efficiency requirements, which can result in significantly higher costs and may also discourage potential buyers from installing solar PV systems, especially if there are no sufficiently qualified/experienced contractors available to install such systems. In addition, as previously mentioned, standard roof-mounted solar panels will add an additional load to the roof that, although usually reasonable for mounting onto a pre-existing roof, may or may not be well suited for each individual case. Current BIPV research shows a great deal of promise to offset or even eliminate these disadvantages in the near future, but not all of these newer BIPV technologies have yet been developed to their full potential, and their market penetration (particularly in the U.S.) is still marginal at best.

Lastly, with respect to GRIPV systems, the primary source of policy resistance is believed to be the current lack of concrete data and information as to the practical extent of the benefits and challenges of such systems. Although green roofs and solar energy have each been researched and developed extensively as separate forms of green infrastructure, the potential interactions between green roof vegetation and solar PV systems have not yet been researched to the same extent, while much of the currently available research and experimentation on GRIPV systems has not yet been adequately replicated and thereby limits the ability of researchers and contractors to make meaningful inferences about these interactions and how they might affect GRIPV system performance (Schindler et al. 2016). As a result, when considering whether or not to install a GRIPV system or implement a GRIPV-focused policy, today's building owners and policy-makers typically need to rely on limited research data and/or generalized assumptions based on knowledge regarding green roofs and solar PV energy individually, while potentially significant benefits and/or problems are often not recognized until after a particular GRIPV roof has already been installed, the latter of which can lead to technical issues and may even require part or all of the roofing system to be replaced. This, in turn, further hinders the market penetration of GRIPV systems in the alternative roofing industry, especially in countries such as the U.S., where building owners and contractors are still relatively inexperienced with such systems and current GRIPV market penetration is virtually nonexistent.

For reasons to be discussed in more detail in the literature review (Section 2.2), these limitations and their impacts on the potential long-term benefits of the alternative roofing industry as a whole have not yet been fully understood in today's literature. Hence, this study will attempt to investigate these impacts in greater detail on a long-term basis, particularly with respect to the following commonly cited environmental and practical benefits with respect to green roofs, solar PV roofing, and/or GRIPV roofing systems:

- *The reduction of urban runoff* through the use of green roofs and/or GRIPV systems, which effectively simulate natural landscapes to certain degrees in order to reduce runoff flow rates in a similar manner,
- *The mitigation of the UHI effect* by green roofs and/or by solar panels individually as well as in a GRIPV roof, either by reflecting/dissipating more heat away from the surface to maintain relatively steady temperatures, or (in the case of solar panels and GRIPV systems) by effectively redirecting a portion of the sun's energy into electricity production instead of absorbing and releasing it as heat,
- *The reduction of energy dependence* on non-renewable fossil fuels by reducing the need for grid-based electricity for HVAC purposes by reducing heat fluxes in and out of the building and/or (in the case of solar panels and GRIPV systems) by producing renewable electricity to further offset the need for grid-based energy, and
- *The subsequent reduction of GHG emissions* due to carbon sequestration by green roof vegetation and/or the above-mentioned reductions in grid-based energy demand.

1.3 Objectives of This Study

The primary aims of this study are as follows:

- To analyze the alternative roofing market (specifically with respect to green roofs, solar/BIPV roofing, and GRIPV roofs) in the city of Orlando, F.L. on a long-term basis, including the overall potential benefits thereof with respect to urban runoff, the UHI effect, energy consumption rates, and GHG emissions,
- To investigate the most likely sources of policy resistance in Orlando with respect to the market penetration rates of green, solar/BIPV, and GRIPV roofing systems and the extent to which this policy resistance may be hindering each industry, and
- To explore the potential of different policy solutions (investments in financial incentives, technological development, public education, alternative roofing bylaws, etc.) to counteract this policy resistance, which will thereby maximize the possible long-term benefits of the alternative roofing market in Orlando.

To this end, the following specific research questions must be addressed regarding the green roof market, the solar PV industry, and the current and future applicability of GRIPV systems, particularly in Orlando:

- What are the most significant obstacles in today's green roof, solar PV, and GRIPV industries?
- To what extent do these obstacles hinder the market penetration of green roofs, solar PV systems, and/or GRIPV roofing?

- How do these obstacles ultimately affect the long-term ability of each alternative roofing option to address the problems that they are each intended to solve, specifically with regards to…
    - Urban runoff?
    - The UHI effect?
    - Energy security?
    - GHG emissions, especially from the electric power sector?
- With respect to solar PV and GRIPV systems specifically, how can more recent trends toward more practical BIPV system designs ultimately help to offset the limitations of current solar PV technologies?
- What can today's policy-makers do to improve the feasibility and overall effectiveness of green roofs, solar PV roofing, and/or GRIPV systems as viable green infrastructure options?
- To what extent can these policy solutions counteract the current degree of policy resistance in the alternative roofing market and maximize the long-term environmental and practical benefits of the different alternative roofing options considered in this study?

The contribution of this study to the existing literature is described in more detail in Section 1.3.1. The remainder of this dissertation is structured as follows:

- *First*, existing literature on alternative roofing (green roofs, solar PV/BIPV roofing, and GRIPV systems) and on applications of diffusion models in System

Dynamics is reviewed (with relevant data values summarized where appropriate), and any observed research gaps are identified and discussed as necessary.

- *Second*, the construction of the Causal Loop Diagram in this study is discussed in detail, including the selection of endogenous and exogenous variables, the drawing of the CLD itself, and analysis of feedback loops.
- *Third*, any and all necessary information for model development and validation (calculations, reference modes, case studies, additional relevant data, etc.) are presented and discussed in detail.
- *Fourth*, a Stock-Flow Diagram is developed in Vensim based on the data and calculations previously discussed.
- *Fifth*, a step-by-step validation process is conducted using the above-mentioned reference modes and other validation tests as applicable, with statistical analyses included as necessary.
- *Sixth*, the finalized SD model is used to simulate the system as part of a series of exploratory analyses, including a basic iterative "policy analysis" based on average data values, as well as a Monte Carlo simulation to explore any potential degrees of uncertainty in this analysis based on possible variations in data values.
- *Seventh*, the results of the above-mentioned policy analyses are summarized and discussed, and appropriate conclusions are drawn accordingly, including discussions on the limitations of this study and possible recommendations for future research on this topic.

1.3.1 Contribution to Literature

Notable contributions of this research to current literature include the following:

- This study provides a comprehensive analysis of the alternative roofing market in an urban U.S. city on a long-term basis, including specific benefits and considerations with respect to three distinct alternative roofing options (green, solar, and GRIPV), as well as how these external and internal influences in the alternative roofing market can affect market penetration rates, competitiveness between different options, and the overall long-term benefits within the roofing industry as a whole.
- The non-economic practical challenges and considerations associated with green roofs, solar/BIPV roofing, and GRIPV roof systems (additional roof loads, lack of contractor experience, etc.), which have been frequently cited in industrial reports on green roofs and solar arrays individually but seldom analyzed in any significant detail, will be included in the SD model developed in this study in order to evaluate their potential impacts on adoption rates for each alternative roofing option.
- Current green roof literature is still very fragmented, with most studies focusing only on one separate aspect of the green roof industry at a time, and is still primarily limited to small-scale, short-term analyses that typically cover time periods of 1 to 2 years at most. Hence, the use of the SD method will allow this study to fill these literature gaps by synthesizing available knowledge on the

green roof industry and simulating green roof market penetration and all relevant factors over longer periods of time.

- Although solar PV market penetration has already been analyzed from a SD perspective in multiple studies, the solar PV industry has mostly been studied as a stand-alone market in the field of renewable energy, with solar PV energy and fossil fuel energy as the only two options, while more specific potential applications of solar PV systems (e.g. BIPV applications) are mostly ignored. This study aims to address this literature gap by analyzing the solar PV market (specifically as roof-mounted systems and BIPV roofing options) in conjunction with that of an additional green infrastructure option (green roofs) as two distinct innovations in a more comprehensive market. Green roof literature can also benefit in a similar way, especially since the green roof industry has never been studied from a SD perspective before.
- Current literature on GRIPV systems is still very limited today (more so than the literature on green roofs and solar PV roofing individually), with emphasis placed mainly on potential improvements in terms of temperature and energy performance while certain other possible benefits (runoff reduction, extended lifetimes for solar PV arrays and/or green roofs, etc.) have tended to receive little to no significant attention in today's research. Although the accuracy of this study's exploratory analyses in this regard is limited due to insufficient available data, this study will nevertheless provide a significant contribution to GRIPV research by integrating current knowledge on GRIPV systems and reasonable

assumptions based on the known benefits and configurations of their individual components (green roofs and solar PV panels) into a holistic analysis of the possible long-term future of the GRIPV market in an urban U.S. city and how local policies with respect to green roofs and solar PV energy individually can help to improve this future.

- Building-integrated photovoltaic systems, especially as improvements over standard roof-mounted solar PV arrays, are still relatively new in the solar PV market, and BIPV applications in literature and in practice are thus very scarce compared to most other solar energy applications despite having a generally optimistic future based on available literature. To address this literature gap and account for the potential growth of the BIPV industry as part of the solar PV market, this model will simulate gradual increases in solar cell efficiency and reductions in solar roofing loads and costs, in turn observing the effects of future BIPV developments on the solar roofing market and, by extension, on the alternative roofing market as a whole and its associated long-term impacts.
- Diffusion models for multiple innovations at a time are still very limited in today's literature and even more so in SD literature, and the developed models can tend to be very complex as more innovations and/or variables are taken into consideration. However, the use of SD modeling in this study allows for the application of a more user-friendly approach to the simultaneous long-term diffusion of more than one innovation without sacrificing scope or detail, and this study will also attempt to simplify the developed model by dividing it into

separate sub-models based on specific impact categories (urban runoff, the UHI effect, energy demand savings, and GHG emission savings), economic and/or practical considerations, and other categories as applicable.

1.4 Dissertation Outline

This dissertation is organized as follows:

- *Chapter One (1) :: Introduction*

Detailed background information is provided with respect to urban runoff, the UHI effect, energy security, and GHG emissions in the U.S., as well as green roofs, solar PV/BIPV energy systems, GRIPV roofing systems, system dynamics, and the study area to be analyzed. The problem statement and corresponding objectives of the dissertation are summarized, and the contributions of the dissertation to existing literature are briefly discussed.

- *Chapter Two (2) :: Literature Review*

Existing literature on green roofs, solar PV systems, BIPV applications, GRIPV systems, and SD innovation diffusion modeling is reviewed, with important findings from the literature summarized as appropriate. Wherever possible, emphasis is placed on critical literature in each individual field. Research gaps are identified based on this literature review, with particular emphasis on the gaps to be addressed in this study.

- *Chapter Three (3) :: Preliminary Research*

Preliminary development steps for the SD model in the dissertation are described in detail, including variable selection, construction of a CLD, analysis of feedback loops, and reference mode data collection. Key equations relevant to runoff, temperature, energy savings, and GHG emission reductions are also presented and discussed in detail. A case study on current examples of green roofs and solar PV arrays in Orlando is conducted Additional required data not previously covered, including historical data and projected future trends, are also summarized and discussed as necessary.

- *Chapter Four (4) :: Model Development*

The development process for the SD model is presented and discussed in detail, including the formulation of the model itself based on the concepts, parameters, and calculations discussed in Chapter 3, as well as the step-by-step validation process used to confirm the structural and behavioral validity of the model for purposes of this study.

- *Chapter Five (5) :: Exploratory Analyses*

The extensive exploratory analyses to be conducted in this study are summarized and discussed in detail, including a standard policy analysis based on average values for relevant non-policy variables, as well as a series of Monte Carlo simulations to account for the inherent uncertainty in the modeled system by examining the full range of all possible results when all possible variations in relevant data values are taken into account.

- *Chapter Six (6) :: Results & Discussion*

The results of the exploratory analyses previously mentioned in Chapter 5 are summarized and discussed in detail, and appropriate conclusions are drawn based on these results. The current limitations of this study are also discussed, along with recommendations for future research on this topic.

CHAPTER TWO (2) :: LITERATURE REVIEW

In this chapter, existing literature on green roofs, solar PV/BIPV roofing, GRIPV roof systems, and SD innovation diffusion modeling is reviewed extensively, with emphasis placed wherever possible on critical literature in each individual field in order to illustrate the full scope of the current literature in each field as much as possible. Important findings on each subject are summarized as needed in each corresponding section, and any and all observed research gaps are identified and discussed in Section 2.2, with particular emphasis on the research gaps to be addressed in this study.

2.1 Summary of Reviewed Literature

More specific literature to be summarized in this literature has been organized into the following three sub-sections:

2.1.1 Green Roofs

2.1.2 Solar Energy & BIPV Technology

2.1.3 GRIPV Roofing Systems

2.1.4 Diffusion Modeling

The available literature reviewed in this study is extensive enough to be able to gain a reasonably realistic perspective of the U.S. green roof and solar PV/BIPV markets, as well as the SD diffusion modeling methodologies to be used in this study, but there are still crucial research gaps to be addressed in this study and in future research. These research gaps will be summarized and discussed in Section 2.2 with respect to all three of the sub-topics listed above.

Applicable data derived from this literature review for modeling purposes will be summarized in Appendix A.

2.1.1 Green Roofs

"Green roofs" in the literal sense (e.g. Scandinavian sod houses) have existed for thousands of years throughout the world in one form or another, but the use of green roofs as a form of green infrastructure, which began primarily in Germany and Switzerland, is much newer in comparison (Magill et al. 2011). Modern green roof research is said to have begun in Germany in the 1960s, when Dr. Reinhard Bornkamm of Berlin first published his work on green roofs in 1961, which would go on to lay the initial groundwork for future green roof studies and applications (Bornkamm 1961). The 1970s saw even further advancement in modern green roof literature with a number of technical research studies, most notably "Roof Areas Inhabited, Viable, and Covered by Vegetation" by Gerda Gollwitzer and Werner Wirsing (Gollwitzer and Wirsing 1971), that contributed greatly to the development of the various key components (root-repelling systems, waterproofing and drainage membranes, etc.) that continue to be widely used in modern green roofs today. In addition, the Landscape Research, Development, and Construction Society (FLL), which was founded in Mainz, Germany in 1975 (Kadlubowski 2007), went on to establish the world's first formal guidelines on green roof design, specifications, and maintenance/testing procedures, which were originally published in German in 1982 and later published in English in 2002 (FLL 2002). The FLL's guidelines are still widely respected to this day and commonly referenced in green roof guidelines in other parts of the world.

Such official standards have only recently begun to emerge in other countries; in the U.S., as of 2013, the American Society for Testing and Materials (ASTM) has only recently officially approved six different standards, each with respect to a different component in a modern green roof, while a more comprehensive standard for green roofs has also been proposed that has yet to be officially approved (Enright 2013). However, despite this relative lack of formal governing standards, growing interest in green roofs has led many universities, government organizations, corporations, and other such groups to contribute significant amounts of research to today's green roof literature, including extensive research on the potential environmental and practical benefits of green roofs, as well as their associated costs and/or savings. Examples of comprehensive literature in this regard include the following:

- In one prominent example (GSA 2011), the United States General Services Administration (GSA) provided a comprehensive review of several potential environmental and economic benefits associated with green roofs, as well as reviews of significant practical considerations and detailed cost-benefit analyses.
- A 2012 report from the National Resources Defense Council (NRDC) provided a generalized review of the potential environmental benefits of green roofs and cool roofs in Southern California, including potential benefits with respect to urban runoff, the UHI effect, energy demand reduction, and air quality improvement (including carbon sequestration), as well as potential cost savings associated with these benefits (Garrison et al. 2012).

- Li and Yeung (2014) published a comprehensive overview of the environmental benefits of green roofs, as well as a review of cost-related concerns and other barriers hindering the market penetration of green roofs in today's industry.

In addition to these more generalized studies, a significant amount of green roof literature has been published that focuses on specific aspects of green roof research in more detail. For organization purposes, these studies will first be briefly summarized, and any observed relevant findings for this study will be listed in separate tables based on general categories. First, reviewed literature specifically pertaining to *urban runoff* includes the following studies (see Table A1 in Appendix A for rainfall retention data from these studies):

- The U.S. Environmental Protection Agency (EPA) published an in-depth report on the benefits of green roofs with respect to runoff volume and water quality, as well as how various plant and media considerations may influence these benefits (Berghage et al. 2009).
- Palla et al. (2010) measured the runoff reduction of a full-scale green roof as well as the percent rainfall volume retention of a smaller "controlled" laboratory test bed in order to evaluate the hydrologic performance of green roofs compared to that of conventional impervious roof surfaces.
- Hathaway et al. (2008) collected experimental data from two separate green roofs in North Carolina in order to analyze their impacts on both runoff volume and runoff water quality (particularly nitrogen and phosphorus concentrations).
- Wanielista et al. (2008) experimented with a variety of green roof designs at the University of Central Florida in order to evaluate the effects of media depth,

drainage layer materials, and pollution control media on runoff flow rates, evapotranspiration rates, and runoff water quality.

- VanWoert et al. (2005) conducted two separate studies, first to compare runoff retention rates in a conventional gravel roof to those in a green roof with and without vegetation, and then to examine the effects of roof slope and media depth on green roof rainfall retention.

Likewise, the following green roof studies have been reviewed specifically with respect to the UHI effect and/or heat fluxes through the roof of a building (see Table A2 & A3 in Appendix A for more detailed literature data), the latter of which will be needed to calculate the resulting changes in HVAC electricity demand:

- Lazzarin et al. (2005) used numerical modeling in conjunction with experimental measurements from a green roof on the Vicenza Hospital in Italy to evaluate the thermal and energy performance of green roofs, with special emphasis on the cooling effects of evapotranspiration from green roofs in the summer. For purposes of this dissertation, most of the thermal characteristics (i.e. density, thickness, and specific heat) of conventional roofs will be modeled based on the parameters specified in Lazzarin et al.'s study, as cited in Section 3.5. Consequently, since the load of a green or conventional roof per unit area can be calculated as density multiplied by thickness, this data will also be used to calculate additional roofing loads from both roof types (excluding standard roofing/support materials).

- Gaffin et al. (2010) performed a seasonal analysis of surface temperatures, heat fluxes into a building, and impacts on heating and cooling costs from conventional roofs, green roofs, and “white roofs” (a.k.a. “cool roofs”) designed to absorb less heat from the sun than conventional roofs.
- Sonne (2006) likewise measured the heat fluxes and surface temperatures of a green roof and a conventional roof on the same building at the University of Central Florida, this time analyzing changes in heat flux and surface temperature for both roof types over the course of any given day, based on averaged data from 2005 to 2006.

Next, with respect to carbon sequestration, Getter et al. (2009) conducted two separate studies to evaluate the carbon sequestration potential of extensive green roofs, including carbon sequestration in the vegetation, roots, and/or substrate. The total green roof carbon sequestration rate observed in Getter et al.’s article are compared in Table A4 alongside the corresponding rates cited in the GSA’s study (GSA 2011).

Lastly, with regard to the more practical considerations associated with green roofs, current green roof literature tends to focus primarily on cost-benefit analyses, roof lifetimes, and potential economic benefits and/or challenges. Examples of such studies, including from articles that have already been cited in this review, include the following:

- Breuning (2016c) performed a cost-benefit analysis of green roofs from the perspective of a commercial buyer, providing a detailed description of investment costs and potential savings for the green roof buyer over the entire lifetime of the green roof in question (estimated at 40 years).

- In an earlier presentation, Breuning (2011) discussed and illustrated several common misconceptions and design/installation mistakes in today's green roof industry, and described how such mistakes can lead to green roof failure and/or inadequate performance.
- The GSA's report (GSA 2011) also performed detailed cost-benefit analyses for installing a green roof instead of a conventional roof for three different roof sizes, including separate analyses for green roofs on the national level and in the Washington, D.C. area, as well as a sensitivity analysis to identify the most significant impacts on the overall cost of a green roof. This report also specifically included detailed summaries of issues regarding heavier and more variable loads from green roofs as opposed to conventional roofs, retrofitting of existing structures with green roofs, relevant codes and standards, contractor selection, safety training, and various specialized practical considerations (plant selection and handling, leak detection, root penetration, etc.).
- The EPA (EPA 2008) provided a generalized review of the practical benefits, costs, loads, and other relevant concerns with respect to green roofs.
- Garrison et al. (2012) briefly discussed the longer roof lifetimes and aesthetic improvements associated with green roofs, and estimated potential overall cost savings of green roofs and/or cool roofs in Southern California at 73-211 million U.S. dollars per year for pre-existing rooftops and 46-131 million U.S. dollars per year for new rooftops and redevelopment.

- Ismail et al. (2012) surveyed nine potential obstacles in Malaysia's green roof industry in order to identify the most critical challenges to overcome with respect to green roof market penetration.

The potential benefits and/or challenges cited in each of these studies have already been discussed in previous sections. Relevant quantitative findings from these studies are summarized in Appendix A. It must be noted that this study will use thermal data from a separate green roof thermal model (Capozzoli et al. 2013), as discussed in more detail in Appendix A; this thermal data includes density and thickness, so to ensure consistency in the physical green roof characteristics to be input into the model, the "average" modeled load for purposes of this analysis will be calculated based on this data (density * thickness), and this calculated load has also been included in Appendix A for comparison with the cited green roof loads from the literature.

The SD model in this study will be initially designed based on average values from the literature cited above, with emphasis on national and/or local data for Orlando, Florida where appropriate. However, these ranges will also be programmed into learning curves and Monte Carlo simulations through Vensim as necessary in order to account for the full range of possible values with all applicable degrees of uncertainty taken into consideration.

2.1.2 Solar Energy & BIPV Technology

As previously noted, despite not yet being sufficiently deployed to overcome the energy sector's current dependence on fossil fuels, solar PV technologies have been researched extensively since the 1970s for a wide variety of purposes. As the United States Department of

Agriculture (USDA) noted in a 2013 report, the available literature on solar PV systems and renewable energy in general, specifically with respect to market penetration of renewable energy technologies, tends to vary based on at least four main categories (USDA 2013):

- The *technologies and/or technology types* being analyzed,
- The *level of aggregation* (individual, local, state, federal, etc.) being considered,
- The specific *sector* (electricity generation, transportation, residential, etc.) being considered, and
- The *analytical methods* (regression, system dynamics, etc.) being used to evaluate the adoption of the technology in question.

With this in mind, and taking into account the primary focus of this study, the remainder of this literature review will emphasize solar PV applications of system dynamics where appropriate. Further emphasis will also be placed on BIPV systems where possible, including their traditional applications (e.g. roof-mounted solar panels) as well as possible future opportunities for BIPV technologies in research and in practice.

The following System Dynamics studies have been found with respect to the market penetration of solar PV energy in the electricity generation sector:

- Yan (2009) published a thorough SD analysis of the Chinese solar PV market and the use of various policy solutions to counteract its policy resistance and thereby achieve the solar PV installation goals of the Chinese government by the year 2020, including policy analyses and analyses for sensitivity and policy robustness.
- Hsu (2012) likewise developed a SD model to analyze the effects of capital subsidies and feed-in tariffs on the market penetration of solar photovoltaic (PV)

systems in Taiwan up to the year 2030, as well as the corresponding reductions in greenhouse gas emissions.

- In Massachusetts, Flynn et al. (2010) used SD modeling to simulate and analyze the state's Solar Renewable Energy Certificate (SREC) market as a means to encourage higher solar PV installation rates in accordance with the applicable Renewable Portfolio Standards (RPSs).
- In a similar study by Movilla et al. (2013), the solar PV energy market in Spain was analyzed up to the year 2020, including analyses of subsidies and the enhanced development (i.e. capacity & efficiency) of future solar PV technologies.

In all four of these studies, it is immediately apparent that the use of financial incentives (subsidies, feed-in tariffs, etc.) will play an essential role in future policy efforts in the solar PV market, so the inclusion of such financial incentives will be implemented into the SD model in this study as explained in later sections, particularly in the form of carbon tax rates and investments of certain percentages of the GDP into the provision of financial incentives. Another potentially vital policy initiative could involve the improvement of current solar PV technology; in Movilla et al.'s study, this improvement was modeled as a reduction in the cost per kWh of solar PV electricity, whereas such technological improvements will be modeled in this study more directly as efficiency improvements over time, while also including a modeled learning curve in solar PV costs based on available historical values and future projections. In this regard, technological improvements corresponding to the future development of BIPV technology will play an important role.

Unlike traditional solar PV technologies, which have been researched and developed extensively since the 1970s, BIPV technological development and market penetration are both still in their early stages, especially in the United States, but BIPV research has quickly begun to gain momentum in more recent years:

- In a 2011 report, the NREL published a comprehensive comparison of standard roof-mounted PV systems and three separate types of BIPV systems (James et al. 2011); the BIPV derivative case was found to be cheaper than the standard PV reference case (\$5.02/W versus \$5.71/W), and was also found to be comparable to the PV reference case in terms of efficiency (13.8% versus 14.5%).
- Breivik (2012) published a compilation of three separate articles, each covering current advances in BIPV technology (BIPV foils, tiles, and modules, as well as solar cell glazing products and standard roof-mounted solar modules), possible opportunities for future research and development into new BIPV technologies, and challenges (esp. weather concerns) associated with more recent design efforts to directly integrate BIPV modules into the envelope of a building, respectively. The efficiencies of the cited product examples in the first article ranged between 6% and 22%, while the second and third articles explored the potential for solar PV modules to seamlessly replace conventional construction materials in the future as well as the weather-related conditions that such modules would need to be able to withstand. During the policy analyses in this study, the gradual transition of the solar PV market to more practical BIPV technologies will be

simulated based on these examples, primarily in the form of gradual reductions in solar roofing loads and eventual increases in efficiency.

- On the other hand, Heinstein et al. (2013) reviewed the current BIPV industry in terms of both its potential and its current challenges, most notably the social and economic factors that are prompting many BIPV companies and potential buyers to effectively "give up" by stopping or abandoning BIPV projects. Based on Heinstein et al.'s review, the influences of public education and BIPV contractor experience will need to be taken into consideration in this study, and will therefore be included as policy variables in the exploratory analyses in Chapter 5.
- As a final example, Schuetze (2013) listed and discussed a series of support policies to address the "technical" (practical) and/or "formal" (aesthetic/creative) appeal of BIPV systems and how each of the two aspects influence public perception of the use of BIPV technology, which in turn affects the BIPV market. In this regard, feed-in tariffs and their associated technical and feed-in tariffs in Germany and France are summarized along with their associated technical and location-based criteria. Although the aesthetic aspects of BIPV system design are very difficult to model properly in SD modeling due to the highly subjective nature of aesthetic quality, Schuetze's study once again highlights the importance of social factors in the BIPV market, which can be simulated in this study in terms of public education, advertising, and other promotional policies.

Lastly, it is worth noting that additional the potential of solar/BIPV roofing to further reduce energy demand by reducing heat fluxes into buildings. Hence, the following two studies in this regard are briefly summarized below:

- Wang et al. (2006) analyzed the impacts of three different BIPV solar roof setups in China on roof heat transfer and PV energy generation, and found that the use of BIPV solar roofing in a building could potentially reduce heat fluxes in and out of the building in this manner or use the solar electricity that they generate to offset the building's HVAC electrical loads, especially if a sufficient "air gap" (preferably with ventilation) can be provided between the solar roofing and the main roof structure.
- Dominguez et al. (2011) used monthly interior and exterior temperature measurements to analyze the potential of roof-mounted solar PV systems to reduce heat fluxes in San Diego, C.A., and calculated the average monthly heating and cooling load requirements for a typical roof with and without the added solar PV system. Monthly cooling loads could be reduced by up to 4.8 W/m^2 on average with the added PV system, although the corresponding net annual reduction was somewhat more modest at 3.17 W/m^2.

The observed heat fluxes in each of these studies have been added to Table A3 in Appendix A. Additional solar/BIPV roofing characteristics will be summarized and discussed as needed in Appendix D, including estimated learning curves based on historical data and potential future projections where available.

2.1.3 GRIPV Systems

The first critical study on GRIPV systems was conducted in Germany on a solar PV array installed in 1999 above part of the pre-existing green roof area of the UFA Factory in Berlin, including fixed and solar-tracking PV modules. Köhler et al. presented a preliminary comparison at the RIO 02 conference of the PV panels' performance above the green roof area and above a conventional roof area on the same building, as well as an evaluation of the impact of the PV panels on plant growth, plant cover, and the number of plant species on the green roof area (Köhler et al. 2002). A follow-up report presented in 2007 (Köhler et al. 2007) further contributed to the UFA Factory experiment by adding experimental data from later years up to 2006, allowing for a more long-term analysis of the overall benefits to the system in question. Köhler et al.'s work laid the foundation for a number of modeling and experimental studies published in later years, and although the available literature on GRIPV systems is still very limited as of 2016 (Schindler et al. 2016), GRIPV systems have continued to gain popularity in recent literature and have also recently become commercially available in North America, although GRIPV systems have not yet become prevalent in the U.S. green infrastructure market.

Most published GRIPV literature focuses on the effects of vegetation (esp. green roof vegetation) on the power output of a solar PV module mounted above the vegetation, or on the overall potential benefit of a GRIPV system in terms of temperature and/or energy performance, although the influence of solar PV arrays on green roof plant communities has also received a relatively fair amount of attention in the literature, such as in Köhler et al.'s research as previously described. Other examples of GRIPV literature include the following:

- At the University of Lleida in Spain, Chemisana and Lamnatou (2014) compared the performance of a standard "reference roof" consisting of a solar PV module placed above a gravel roof with those of two similar PV modules each placed above a wooden box containing a different type of vegetation commonly used in green roofs (*Sedum clavatum* and *Gazania rigens*), specifically comparing the modules to one another in terms of voltage, temperature, irradiance, and other relevant parameters. Chemisana and Lamnatou also analyzed GRIPV systems from a life-cycle perspective based on observed PV output gains from the literature and compared the results to those of extensive and intensive green roofs without PV panels (Lamnatou and Chemisana 2014), and later compiled a more in-depth review of key factors, benefits, and possible policy initiatives (e.g. subsidies) with respect to GRIPV systems, including discussions on albedo and the selection of suitable plants for the GRIPV system (Lamnatou and Chemisana 2015).
- Witmer (2010), as part of his thesis at Pennsylvania State University, created a GRIPV energy balance model using the software TRNSYS with inputs for applicable system-specific parameters and U.S. region-specific data, and used this model to analyze the energy performance (esp. efficiency and power production) of GRIPV systems compared to standard PV arrays above black and white conventional roofs, including potential regional variations as well as the effects of the percentage of solar PV coverage (the fraction of the GRIPV roof that includes solar PV panels) on the net present value of a GRIPV system.

- Another thesis at Portland State University (Ogaili 2015) also analyzed and compared different roof types (green, conventional black, and conventional white) with integrated solar PV arrays, but this time used experimental testing with PV panels mounted over the corresponding roof surfaces to find and compare the convection coefficients, temperatures, and PV power outputs of each option. In a separate experiment within the same thesis, Ogaili also mounted the PV panels at either 24 cm or at 18 cm in order to evaluate the impacts of PV panel height on the PV system performance of each option.
- Hui and Chan (2011) used the simulation software EnergyPlus to explore the impacts of four different roof configurations (bare roof, roof-mounted solar PV array, green roof, and GRIPV roof) on the monthly and annual energy performance levels of a typical building. In addition to these simulations, Hui and Chan also used field measurements on identical PV panels on actual bare roof and green roof surfaces at Hong Kong University to analyze soil surface temperatures on green roofs with and without the inclusion of a solar PV module, as well as the energy efficiency gains of solar PV arrays with and without an integrated green roof system. Lastly, in order to evaluate the practical and economic design issues associated with GRIPV systems, a case study involving the hypothetical retrofitting of a roof with a standard PV array to include integrated green roofing was also taken into account, and the annual energy-related cost savings with respect to both the pre-existing solar PV system and the integrated green roof component were calculated accordingly.

- Using EnergyPlus and available weather-related data, Scherba et al. (2011) simulated and analyzed the temperatures and heat flux rates of conventional roofs (black and white) and green roofs in six different U.S. cities, with each roof type analyzed with and without an integrated PV system. The six selected U.S. cities corresponded to five different "climate zones" in the U.S., with the city of Houston, T.X. located in the same climate zone as Orlando, F.L.
- Schindler et al. (2016) provided a comprehensive review of the GRIPV literature to date, including many of the studies previously discussed, as well as additional literature on external topics with potential applicability to GRIPV systems (effects of shading on green roofs, impacts of solar PV systems on the plant and animal communities on a green roof, etc.). This review and that of Lamnatou and Chemisana (2015) both provide detailed summaries of GRIPV energy efficiency improvements observed on the literature, while also clearly identifying the most critical research gaps in GRIPV literature and other potential areas of research for GRIPV to explore.

GRIPV energy efficiency gains from the literature are summarized in Table A8 in Appendix A, and other available data on benefits and other relevant parameters with respect to GRIPV systems is summarized in Appendix D. Reasonable assumptions based on green roofs and solar PV panels individually will also be incorporated into the model in this study as necessary to ensure consistency among all three alternatives and to account for any missing data; these assumptions will be discussed further in Section 4.1.

2.1.4 Diffusion Modeling

The primary objective of this study is to use a System Dynamics methodology to develop an innovation diffusion model for the alternative roofing market in Orlando, F.L., specifically with respect to the adoption of green roofs, solar PV/BIPV roofing, and GRIPV systems as alternatives to conventional roofs. Hence, the two critical aspects to be addressed in this literature review are:

- *Diffusion modeling applications in system dynamics*, and
- *Diffusion modeling with multiple innovations*.

First, although the SD method was originally developed in the 1970s (Forrester 1971), research on the diffusion of innovations has roots dating as far back as the late 19th century (Kinnunen 1996), and was first widely implemented in rural sociology in the 1920s and 1930s (Valente and Rogers 1995). However, the first concrete paradigm in product diffusion research was ultimately established in Ryan and Gross' hybrid seed corn study in the 1940s (Ryan and Gross 1943), which would lay the basic foundations for later diffusion studies. Nevertheless, applications of innovation diffusion theory continued to remain mostly limited to the field of rural sociology until Everett Rogers published "Diffusion of Innovations" in 1962, which popularized the concept of diffusion theory and helped to synthesize diffusion research from different areas of sociology, contributing to the subsequent expansion of diffusion research and applications beyond their origins in rural sociology and into various other fields; "Diffusion of Innovations" has been updated consistently since then, with its most recent edition having been published in 2003 (Rogers 2003).

The adoption of a new product or innovation over time is subject to many direct and indirect influences at any given time, including (but not limited to) prices, availability, public perception, and other external factors. This makes SD modeling very well suited to diffusion modeling applications, as the systems thinking approaches necessary for SD modeling allow the SD methodology to simultaneously analyze all of the relevant influences and impacts with respect to the innovation being considered, including many indirect or external influences that otherwise might not be taken into account. Examples of published studies in this regard (not including the solar PV diffusion studies already discussed in Section 2.1.2) are listed below:

- Baran (2010) established a basic template for modeling the Bass Diffusion Model in system dynamics, as previously discussed in Section 1.1.7.
- Lane and Husemann (2004) developed a modified Bass Diffusion Model with which to simulate cinema ticket sales and analyze potential movie marketing strategies, accounting for failed diffusion due to loss of interest and/or "moving on", as well as influencing factors (e.g. "appeal") and dynamic advertising strategies as policy solutions.
- Santa Eulalia et al. (2011) analyzed the German electric vehicle market using a combination of the Bass Diffusion Model and discrete choice modeling, by replacing the "advertising" and "word-of-mouth" coefficients in the traditional Bass Diffusion Model with a more complex discrete choice sub-model in which utility parameters, customer satisfaction, and other contributing factors are all taken into account. A similar approach is used in this dissertation to extend the

traditional "word-of-mouth" setup in the Bass Diffusion Model to account for the interdependent nature of the alternative roofing market and its benefits.

- Fisher et al. (2000) applied diffusion modeling to decision-making processes in agricultural business management, specifically with regard to the adoption of yield monitoring and yield-mapping technology. Endogenous and exogenous factors featured in the developed model include learning curves, perceived costs and benefits, and support mechanisms, and it is worth noting that the information dynamics sub-model in Fisher et al.'s study is otherwise very similar in structure to the Bass Diffusion Model in that the "perceived benefits" as modeled in the sub-model also includes the influence of advertising and the word-of-mouth effect.

Although these studies cover subject matter not related to this research, the diffusion modeling principles are still very similar to those to be employed in this dissertation. For example, it is worth noting that all of the above-cited studies incorporated the Bass Diffusion Model to some extent, with extensions and modifications added as necessary to make each model more robust and/or more applicable to the topic(s) being covered in each study. Furthermore, many of the basic factors included in each of the above-mentioned studies (advertising, product-specific utility parameters, learning curves, support mechanisms, etc.) will also be present in the system to be modeled in this dissertation, as explained above and discussed further in later chapters, and can therefore be subjected to similar policy analyses to encourage greater adoption rates in a similar manner.

Because this dissertation will also feature simultaneous diffusion modeling of two distinct innovations (green roofs and solar/BIPV roofing), diffusion modeling applications for multiple innovations have also been reviewed, including non-SD studies. Applicable diffusion modeling studies in this regard include the following:

- Meyer and Winebrake (2009) developed a SD model called "H_2VISION" (Hydrogen Vehicle and Infrastructure Simulator for Integrated and Operational Transportation Networks) to evaluate the simultaneous market penetration of hydrogen vehicles and hydrogen vehicle fueling infrastructure as complementary goods, as one cannot be successfully adopted in practice without the other. As with most diffusion models, the H_2VISION model accounted for vehicle, fuel, and infrastructure prices, as well as government purchases of hydrogen vehicles, but also included feedback loops between the availability of vehicle fueling infrastructure (modeled as the "density" of fueling stations within a fixed area) and the purchase rates for the corresponding vehicles, as well as a carrying capacity for fueling stations depending on vehicle demand estimates, which in turn affects the construction rates for new fueling infrastructure.
- Wang and Chang (2009) used a hybrid Genetic Algorithm (GA) approach to formulate a modified diffusion model for multiple products, which was then applied to two different examples: different types of milk packaging (glass, paper, and plastic), and global sales of different sizes of LCD monitors. The resulting model focused primarily on price competitiveness between each of the options considered, while also including the standard "advertising" and "word-of-mouth"

coefficients from the Bass Diffusion Model, as well as additional parameters from later variations of the Bass Diffusion Model.

- As a final example, Rossman et al. (2008) introduced a multilevel diffusion curve methodology to model the diffusion of several innovations at once, and then applied this methodology to broadcasts of as many as 534 pop songs at a time in order to identify and/or measure the effects of "payola" (bribery in exchange for giving more "regular" air time on commercial radio to certain songs at the expense of other songs) on the broadcast (i.e. adoption) rates for each song. More specifically, the methodology in question used multilevel regression analysis to formulate the diffusion curves, accounting for parameters related to "holiday season" releases, whether or not the song in question is implicated in payola, and other relevant factors as applicable.

Again, although these studies cover subject matter not related to this research, the interactions between the different options being considered and the influences of the system as a whole include key similarities to the system to be modeled in this study, especially as exploratory analyses are conducted to evaluate how much focus should be given to green roofs and/or solar PV/BIPV roofing in policy implementations. For instance, the effects of carrying capacity and government support from the H_2VISION model (Meyer and Winebrake 2009) will be applied to this dissertation in a similar manner; more specifically, two distinct carrying capacities will be applied to the system modeled in this study based on the overall degree of urban development and the total available land area for such urban development in the city of Orlando, while government support (especially in the form of financial incentives) will be applied in the SD model for this study as fractions of Orlando's local GDP, thus evaluating the economic feasibility of such financial incentive policies by evaluating the degrees to which the city of Orlando can invest in the alternative roofing market. In addition, as in Wang and Chang's and Rossman et al.'s studies, direct competitiveness between conventional, green, and solar roofing options will also be taken into consideration in this dissertation, specifically in terms of practical considerations such as price per unit area, roofing loads, and roof lifetimes. Lastly, it is worth noting that Wang and Chang's study once again features a variation of the Bass Diffusion model and thus incorporates many similar principles in the resulting diffusion model, particularly in terms of prices, advertising, and the word-of-mouth effect.

2.2 Gaps in Current Literature

Notable research gaps in the current literature on green roofs, solar/BIPV technology, and simultaneous diffusion modeling for multiple innovations are briefly summarized below:

- Current green roof literature is still very fragmented, with most studies focusing only on one separate aspect of the green roof industry at a time, and is still primarily limited to short-term analyses that typically cover time periods of 1 to 2 years at most. As a result, most comprehensive guidelines and industrial reports on green roofs are usually sufficiently detailed to provide a generalized picture but cannot adequately evaluate the long-term impacts of the green roof market as a whole. On the other hand, most journal articles and other works in the literature that cover green roofs over any given time period tend to consist of detailed analyses on one or more specific benefits and/or considerations with respect to green roofs on an individual basis, resulting in a thorough but short-term exploration of the specific areas covered in each study on a small-scale basis, while many other considerations and any long-term impacts on society as a whole are either only briefly mentioned or ignored altogether.

- Although solar PV market penetration has already been analyzed from a SD perspective in multiple studies, the solar PV industry has mostly been studied as a stand-alone market with respect to renewable energy, with solar PV energy and fossil fuel energy as the only two options. Consequently, SD analyses of solar PV adoption tend to focus on the adoption of solar PV as a renewable energy resource while also ignoring the potential for additional specific applications (e.g. BIPV roofing) to further enhance market penetration.
- GRIPV systems, despite showing considerable promise in recent literature and in the few practical examples available to be a viable combination of green roofs and solar PV modules, are still relatively new to the alternative roofing market (especially in the U.S.) and still have significant research gaps that must be addressed more thoroughly before their challenges and potential benefits can be fully understood. Most notably, while the effects of the green roof component on the solar PV component (PV energy efficiency gains, cooling of PV panels, etc.) has been theoretically modeled and experimentally measured to an extent, many of these studies lack the replication plots needed to make any strong inferences about the actual performance of a GRIPV system in a particular location under a given set of conditions. In addition, potentially critical impacts of the solar PV

component on the green roof component (e.g. plant growth and diversity) have been largely neglected in current GRIPV literature, having only been numerically quantified in a relatively small number of studies. Lastly, the reviewed literature on GRIPV systems consists primarily of theoretical modeling studies and mostly small-scale experiments, few of which were conducted on a long-term basis, and this coupled with the lack of substantial GRIPV market penetration (esp. in the U.S.) has limited inferences regarding the possible long-term future of the GRIPV market and/or the long-term impacts of GRIPV systems.

- Building-integrated photovoltaic systems, especially as improvements over standard roof-mounted solar PV arrays, are still relatively new in the solar PV market, and these newer BIPV applications in literature and in practice are thus very scarce compared to most other solar energy applications despite having a generally optimistic future based on available literature. To address this literature gap and account for the potential growth of the BIPV industry as part of the solar PV market, this model will simulate gradual increases in solar cell efficiency and reductions in solar roofing loads, in turn observing the effects of future BIPV developments on the solar roofing market and, by extension, on the alternative roofing market as a whole and its associated long-term impacts.
- Among potential hindrances to the green roof and solar/BIPV markets, emphasis in today’s literature is placed primarily on economic obstacles (e.g. high initial costs), while non-economic practical challenges and considerations (additional roof loads, lack of contractor experience, etc.) have been frequently cited in

industrial reports (Breuning 2011; GSA 2011) but have seldom been analyzed in any significant detail. Consequently, the challenges facing the green roof and solar/BIPV industries are analyzed from an incomplete perspective, which is especially problematic because many of these non-economic obstacles in reality can lead to roof failures and other problems while also discouraging potential alternative roof adopters.

- Diffusion models for multiple innovations at a time are still very limited in current literature and even more so in SD literature, and the developed models can tend to be very complex as more innovations and/or variables are taken into consideration. However, the use of SD modeling in this study allows for the application of a more user-friendly approach to the simultaneous long-term diffusion of more than one innovation without sacrificing scope or detail, and this study will also attempt to simplify the developed model by dividing it into separate sub-models based on specific impact categories (urban runoff, the UHI effect, energy demand savings, and GHG emission savings), economic and/or practical considerations, and other categories as applicable.

Each of these research gaps has already been noted in Section 1.3.1, and can be thusly addressed in this study by providing a comprehensive analysis of the alternative roofing market in the city of Orlando on a long-term basis. This includes in-depth analyses of specific benefits and considerations with respect to each of the considered roofing options, as well as how these external and internal influences in the alternative roofing market can affect their respective market penetration rates, competitiveness among all three options (conventional, green, and solar roofing), and the overall long-term benefits with respect to the alternative roofing industry and its associated environmental and socioeconomic impacts. In addition, in light of the current limitations on available data and literature with respect to GRIPV systems, this limited data can be used in conjunction with current knowledge on green roofs and solar PV energy individually to derive reasonable estimates for any missing data/parameter values.

CHAPTER THREE (3) :: PRELIMINARY RESEARCH

This chapter covers the preliminary research and development steps for the SD model to be developed and implemented in this study, including case studies of individual examples of the alternative roofing systems to be considered, the conceptualization of the system to be modeled, a thorough review of the associated feedback relationships to be incorporated into the model and targeted in relevant policy analyses, the reference modes to be used to statistically confirm the behavioral validity of the finalized model, and discussions of primary calculations and additional data requirements to be incorporated into the model. Hence, this chapter will be divided primarily into one section for individual roofing case studies and two sections discussing each preliminary development step. All of these sections are summarized below:

- Alternative Roofing Case Studies (Section 3.1)
- Variable/Parameter Selection (Section 3.2)
- Construction & Analysis of a Causal Loop Diagram (Section 3.3)

3.1 Real-World Alternative Roofing Case Studies

The main focus of this study is on the alternative roofing market in Orlando, F.L., specifically with respect to green roofs, solar PV/BIPV roof systems, and GRIPV systems. However, it must be noted that the potential challenges and performance levels of all three of these roofing options are significantly dependent on the specific local climates and pre-existing markets and policies in a particular city or region. The performance of a green roof, for example, depends heavily on the growth and overall condition of the vegetation to be planted on the roof, while the performance of a solar PV or BIPV system will depend on the PV modules' regular degree of exposure to sunlight. Likewise, although the U.S. GRIPV market has recently made some degree of progress in New York City (Breuning 2013), GRIPV systems are otherwise virtually unheard of in the U.S. even though they continue to gain popularity in today's green infrastructure research. Therefore, in order to gain a more practical understanding of Orlando's alternative roofing market and thus identify the most common challenges and benefits to be modeled and analyzed in this study, it is important to analyze real-world examples of the roofing options to be considered in this study, especially in Orlando. For this purpose, a case study has been conducted with respect to a number of green roofing and solar PV projects in Orlando, collecting data on real-world alternative roofing systems in Orlando that may be integrated into the SD modeling and analyses to be performed later into this study.

The following buildings in Orlando have green roof systems that will be included in this case study:

- University of Central Florida (UCF)
    - Student Union
    - Stormwater Management Academy
- New American Home 2007

Likewise, the following buildings and locations in Orlando have roof-mounted solar PV arrays (including one location that also has a solar canopy) that will also be included in this case study:

- Orange County Convention Center
- Darden Restaurants Support Center

Although no known GRIPV roof systems have yet been installed in Orlando, one known examples of a GRIPV system in practice (NYC Parks' 5-Borough Administration Building in New York City, N.Y., U.S.A.) also been included in this case study in order to evaluate the potential advantages, disadvantages and/or disadvantages in Orlando for future GRIPV market penetration rates. Data from these real world alternative roofing cases that can be readily applied to the SD model in this study has been summarized in Appendix C.

3.2 Selected Variables for Analysis

Based on the reviewed literature discussed in Chapter 2 and the real-world case studies summarized in Section 3.1, there are a wide range of environmental, socioeconomic, and practical variables that can influence the alternative roofing market. With respect to the SD model to be developed, these variables can be divided into two primary categories based on their connections to other variables and to the developed model as a whole:

- *Exogenous variables* representing external factors not directly dependent on any other variable in the model, and
- *Endogenous variables* directly connected to one or more other variables in the model.

However, due to the inherently macro-level scale of any System Dynamics analysis, not all variables that might potentially influence the modeled system in reality can realistically be included in a SD model without making the model more complicated than necessary for a particular analysis. Consequently, the model must be limited to a more realistically usable scope while still accounting for the relevant parts of the modeled system with respect to the analysis being performed, meaning that some variables must be excluded for simplification purposes. Finally, based on the variables selected for inclusion in the model, a set of more detailed parameters can be included in the Causal Loop Diagram (CLD), which will serve as the primary conceptual framework for the model development process.

To further simplify the developed SD model for purposes of this study, the full model will be split into the following sub-models, each of which represents a different aspect of the system as a whole:

- The *land expansion sub-model*, which simulates the total land area of the city of Orlando and the amount of available land area for future development,
- The *new construction & main diffusion sub-models*, which work together to simulate the effects of population on new roofing development over time and the adoption processes for each of the alternative roofing options to be considered, respectively,
- The *urban runoff sub-model*, which simulates the average overall runoff depth based on the Annual Storm Runoff Coefficients (ASRCs) of each roof type, as well as the societal concerns in the city of Orlando with respect to urban runoff,
- The *urban heat island sub-model*, which simulates the UHI effect as a function of the thermal properties and cooling effects of different roof types, as well as the societal concerns in the city of Orlando with respect to the UHI effect,
- The *energy sub-model*, which simulates the energy savings and/or energy generation from alternative roof types (green roofs, solar PV/BIPV roofing, and GRIPV roof systems), as well as the overall contributions of all such alternative

roofing systems to the desired energy demand reductions for the established targets and goals for the city of Orlando,

- The *energy sub-model*, which simulates the energy savings and/or energy generation from alternative roof types (green roofs, solar PV/BIPV roofing, and GRIPV roof systems) relative to conventional roofs, as well as the overall contributions of all such alternative roofing systems to the desired energy demand reductions for the established targets and goals for the city of Orlando,
- The *GHG sub-model*, which simulates the GHG emission savings from alternative roof types (green roofs, solar PV/BIPV roofing, and GRIPV roof systems) relative to conventional roofs, as well as the overall contributions of all such alternative roofing systems to the desired GHG emission reductions for the established targets and goals for the city of Orlando,
- The *economic sub-models* for each roof type, which work together to simulate the overall cost effectiveness of each alternative roof type (green roofs, solar PV/BIPV roofing, and GRIPV roof systems) as a function of costs, operational savings, and financial incentives,
- The *practical sub-models* for each roof type, each of which simulates the overall practicality of each alternative roof type relative to other available roof types as a function of roof lifetime, roof loading, and contractor experience with each alternative roof type, and
- The *word-of-mouth sub-model*, which synthesizes the results of all of the environmental, socioeconomic, and practical sub-models listed above to simulate

the overall impact of all external factors on the adoption rates of each alternative roof type, particularly in terms of the overall demand for alternative roofing and the overall attractiveness of each alternative roof type relative to all other available roof types.

The finalized lists of parameters to be included in each sub-model are summarized in Tables 8 through 17. A full summary of all selected or excluded variables for each sub-model is provided in Appendix B.

First, parameters corresponding to the total and undeveloped land areas are listed Table 8. The total land area represents the overall carrying capacity for urbanization in the city of Orlando, while the undeveloped land area indicates land area that is still available for new roofing development. For obvious reasons, this sub-model is directly connected to the main diffusion model, so for purposes of this study, it is assumed that all new land expansion starts as undeveloped land.

Table 8: Land Area & Expansion Parameters

Parameter Information	*Type*	*Units*	*Description*
Net Land Expansion	Endogenous	Acres/Year	Net Annual Increase in Total Land Area
Net Land Expansion Rate	Exogenous	DMNL[1]	Net Annual Growth Rate in Total Land Area
Total Land Area	Endogenous	Acres	Total Area of Land Within Study Area
Conventional Roof Area	Endogenous	Acres	Total Area of Conventional Roofing Within Study Area
Green Roof Area	Endogenous	Acres	Total Area of Green Roofing Within Study Area
GRIPV Roof Area	Endogenous	Acres	Total Area of GRIPV Roofing Within Study Area
Solar Roof Area	Endogenous	Acres	Total Area of Solar PVBIPV Roofing Within Study Area
Undeveloped Land Area	Endogenous	Acres	Total Area of Undeveloped Land Within Study Area

[1]Dimensionless

Next, parameters corresponding to population and the initial construction and development in the study area are summarized in Table 9. For purposes of this study, given the predominance of conventional roofs in Orlando's roofing industry, it is assumed that all new roofing construction begins as conventional roof area. Furthermore, the initial population has been included as an exogenous variable in order to make this portion of the model easier to adjust as needed for different starting years.

Table 9: Population & New Construction Parameters

Parameter Information	*Type*	*Units*	*Description*
Net Population Change	Endogenous	Persons/Year	Net Annual Change in the Population of the Study Area
Net Population Change Rate	Exogenous	DMNL[1]	Net Annual Change Rate in the Population of the Study Area
New Roofing Construction	Endogenous	Acres/Year	Net Annual Increase in Developed Area
Non-Residential Construction	Exogenous	DMNL[1]	Non-Residential Annual Development Rate Per Unit of Residential Annual Development Rate
Population	Endogenous	Persons	Total Number of People in the Study Area

[1]Dimensionless

Variables and parameters corresponding to the alternative roof diffusion process and relevant word-of-mouth variables for each alternative roof type will be summarized in Table 10; since these variables and core causal structures are all essentially repeated in the model for each alternative roofing option, they will not be listed individually for each option and will instead be summarized in a single table. These variables are based primarily on the Bass Diffusion Model as previously discussed in Section 1.1.7.1., although the word-of-mouth effect on adoption rates will be covered in more detail in the word-of-mouth sub-model. Because alternative roofing adoption rates in the U.S. are not necessarily directly proportional to the number of persons who use such roofs (mainly because green roofing and solar BIPV energy in the U.S. are currently more commonly used for non-residential buildings), the main diffusion model in this study will be simulated in terms of the roofing area converted to green, solar PV/BIPV, or GRIPV roofing rather than the number of individual persons who install a roof of any particular type, although the construction rate for new roofing will be assumed (as previously discussed) to be proportional to population growth. Other external variables influencing the alternative roof market (specifically the variables “General AltRoof Demand” and “Alternative Attractiveness”) will be listed in their respective tables. Any required non-excluded variable data that has not already been discussed will be summarized in Appendix D. Lastly, in light of the fact that the GRIPV market in Orlando is currently nonexistent, it must be noted that its portion of the model will be inactive until its introduction in the exploratory analyses in Chapter 5.

Table 10: Main Diffusion Parameters For Each Alternative Roofing Option[1]

Parameter Information	*Type*	*Units*	*Description*
Alternative Advertising & PubEd	Exogenous	DMNL[3]	Fraction of Conventional Roof Area Converted to Alternative Roof Area of Type “i” Via Advertising and/or Public Education
Alternative Attractiveness	Endogenous	DMNL[3]	Multiplier Representing the Attractiveness of Alternative Roof Type “i” Relative to Other Roofing Options
Alternative Roof Adoption	Endogenous	Acres/Year	Total Annual Conversion Rate from Conventional Roof Area to Alternative Roof Area of Type “i”
Alternative Roof Area	Endogenous	Acres	Total Developed Area with Alternative Roof Type “i”
Alternative WOM Effect	Endogenous	DMNL[3]	Fraction of Conventional Roof Area Converted to Alternative Roof Area of Type “i” via Word of Mouth
Alt Roofing Contact Rate[2]	Exogenous	Per Year	Annual Number of “Contacts” Between Alternative Roof Owners & Conventional Roof Owners
Alternative Base Purchase Fraction	Exogenous	DMNL[3]	Base Fraction of “Contacts” Conventional Roof Owners and Owners of Alternative Roof Type “i” That Result in the Adoption of Alternative Roof Type “i”
General AltRoof Demand	Endogenous	DMNL[3]	Multiplier Representing the Demand for Alternative Roofing in General

[1]These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.
[2] The contact rate is assumed to be the same for all alternative roofing options.
[3]Dimensionless

Parameters corresponding to urban runoff are summarized in Table 11. This portion of the model serves primarily to calculate "Runoff Concerns", which will be measured by dividing the total annual runoff depth by a "Base Runoff" from a hypothetical all-natural landscape, and which will be one of the public concern parameters that will influence alternative roofing demand in a later sub-model. Runoff-related concerns will primarily influence the adoption of green roofs and GRIPV systems, as solar roofing and conventional roofs are both considered impervious surfaces for purposes of this study.

Table 11: Urban Runoff Parameters

Parameter Information	*Type*	*Units*	*Description*
Annual Rainfall	Exogenous	Inches	Total Annual Precipitation
Average ASRC	Endogenous	DMNL[1]	Average Overall Annual Storm Runoff Coefficient
Annual Runoff Depth	Endogenous	Inches	Total Annual Runoff Depth
Base Runoff	Endogenous	Inches	Hypothetical Total Runoff from a Purely Non-Urban (Pervious) Area with the Same Precipitation
Pervious ASRC	Exogenous	DMNL[1]	Annual Storm Runoff Coefficient from Pervious Areas (Undeveloped Land)
Runoff Concerns	Endogenous	DMNL[1]	Total Runoff / Base Runoff

[1]Dimensionless

Parameters corresponding to temperature and the UHI effect are summarized in Table 12. This portion of the model serves primarily to calculate "UHI Concerns", which will be measured by dividing the air temperature anomaly by the average rural air temperature, and will be one of the public concern parameters that will influence the overall demand for alternative roofing.

Parameters corresponding to the density or thickness of different roofing options will be discussed in more detail in later sub-models.

Table 12: Urban Heat Island Effect Parameters

Parameter Information	*Type*	*Units*	*Description*
Annual Insolation	Exogenous	kWh/(acre-day)	Average Year-Round Daily Horizontal Insolation
Average Cooling Effect	Exogenous	DMNL[1]	Average Overall Cooling Effect of All Developed and Undeveloped Surfaces in Orlando
Average Resistance to Surface Temp Increase	Exogenous	kWh/(acre-^{0}F)	Average Overall Material Resistance to Increases in Surface Temperature of All Developed and Undeveloped Surfaces in Orlando
Average Surface Temp Change	Endogenous	^{0}F	Average Night-to-Day Change in Surface Temperatures in Orlando
Base Surface Temp Change	Endogenous	^{0}F	Average Surface Temperature Change in a Hypothetical All-Natural Landscape
Surface Temperature Anomaly	Endogenous	^{0}F	Difference Between Average and All-Natural Surface Temperature Change Rates
Air Temperature Anomaly	Endogenous	^{0}F	Difference Between Average and All-Natural Air Temperature Change Rates
Rural Air Temperature	Exogenous	^{0}F	Average Air Temperature of the Nearest Known Rural Area (“Clermont 9 S” Station)
UHI Concerns	Endogenous	DMNL[1]	$\frac{Air\ Temperature\ Anomaly}{Rural\ Air\ Temperature}$

[1]Dimensionless

Parameters corresponding to energy demand are summarized in Table 13. This sub-model serves primarily to calculate the overall contributions of the alternative roofing industry with respect to Orlando’s short-term (2018) and long-term (2040) reduction goals/targets for energy demand per capita, which will be included among the public concern parameters that will influence alternative roofing demand in a later sub-model; for purposes of this CLD, however, only the goal progress parameters will be shown, as the variables and causal structures are identical for both targets and goals. This sub-model is also closely related to the GHG sub-model in that reduced energy demand will be a primary contributing factor to GHG emission reductions.

Table 13: Energy Parameters

Parameter Information	*Type*	*Units*	*Description*
Cooling Energy Savings	Endogenous	kWh	Total Reduction in HVAC Electricity Demand for Buildings in Orlando
PV Energy Generation	Endogenous	kWh	Total Solar PV Electricity Production from GRIPV Roof Systems
PV Energy Efficiency	Endogenous	DMNL[1]	Energy Conversion Efficiency of a Solar PV System
PV Energy Development	Endogenous	DMNL[1]	Annual Increase in PV Energy Efficiency
PV Energy Research	Exogenous	DMNL[1]	Annual Rate of Increase in PV Energy Efficiency
Total Energy Savings	Endogenous	kWh	Total Reduction in Electricity Demand
Energy Savings Per Capita	Endogenous	kWh/Person	Per-Capita Reduction in Electricity Demand
Per Capita Energy Savings Goal	Exogenous	kWh/Person	Total Desired Per-Capita Reduction in Electricity Demand by the Year 2040
Energy Goal Progress	Endogenous	DMNL[1]	Contribution of the Alternative Roofing Industry Toward 2040 Energy Demand Reduction Goals

[1]Dimensionless

Parameters corresponding to GHG emissions and emission savings are summarized in Table 14. This sub-model serves primarily to calculate the overall contributions of the alternative roofing industry with respect to Orlando's short-term (2018) and long-term (2040) reduction goals/targets for GHG emissions, which will be included among the public concern parameters that will influence alternative roofing demand in a later sub-model; for purposes of this CLD, however, only the goal progress parameters will be shown, as the variables and causal structures are identical for both targets and goals. As previously noted, this sub-model is also closely related to the energy sub-model in that reduced energy demand will be a primary contributing factor to GHG emission reductions from all three alternative roofing options. Consequently, the GHG sub-model has a simpler basic structure than the energy sub-model, as the GHG emission savings due to reductions in energy demand can be found by simply multiplying the energy savings by the GHG emission reduction factor for Florida's regional power grid. However, the GHG sub-model will also include an additional parameter simulating the carbon sequestration potential of green roofs and GRIPV systems, which is not covered in the energy sub-model because carbon sequestration is independent of energy savings.

Table 14: GHG Parameters

Parameter Information	*Type*	*Units*	*Description*
Power Grid GHG Emission Factor	Exogenous	Metric Tons CO_2/kWh	GHG Emission Savings Per Unit of Emergy Demand Reduced
AltRoof Carbon Sequestration	Endogenous	Metric Tons CO_2	Total Annual Carbon Removal by Green Roofs and GRIPV Roof Systems
Total GHG Emission Savings	Endogenous	Metric Tons CO_2	Total GHG Emission Savings from the Alternative Roofing Industry
GHG Emission Savings Goal	Exogenous	DMNL[1]	Fractional GHG Emission Reduction Goal for the Year 2040
GHG Goal Progress	Endogenous	DMNL[1]	Contribution of Alternative Roofing Industry Toward 2040 GHG Emission Reduction Goal

[1]Dimensionless

Next, parameters corresponding to the different economic sub-models will be summarized in the following tables:

- Financial Incentives (Table 15)
- Cost Effectiveness of Each Alternative (Table 16)

The structures of the economic sub-models for each category will be virtually identical with respect to each roof type, but the numerical values of the parameters included may vary for each roof type. For example, runoff flow rates of solar PV roof systems are assumed to be no different from those of conventional roofs and would therefore yield no significant wastewater cost reductions. Likewise, since the operational costs of a conventional roof are the assumed baseline for these operational savings and it is assumed that no financial incentives are offered for conventional roofing systems, no operational savings or financial incentives are included for conventional roofs, and the Standardized Net Value (SNV) sub-model for conventional roofing will only include the costs of conventional roofs. Therefore, to avoid redundancy for purposes of this CLD, a general sub-model diagram will be used to illustrate the economic sub-model's structure as it applies to each alternative. Lastly, it must be noted that no financial incentives have yet been offered or proposed specifically for GRIPV systems because such systems are still relatively unheard of in today's alternative roofing market; hence, the available incentives for GRIPV systems will instead be modeled as a function of the available incentives for green roofs and solar PV systems.

Table 15: Financial Incentive Parameters

Parameter Information	*Type*	*Units*	*Description*
Net GDP Change Rate	Exogenous	DMNL[1]	Annual Net Fractional Change in the GDP of Orlando, FL
Net GDP Change	Endogenous	US Dollars/Year	Annual Net Change in the GDP of Orlando, FL
GDP	Endogenous	US Dollars	Gross Domestic Product of the City of Orlando, FL
Green GDP Investment	Exogenous	DMNL[1]	Annual Net Fractional GDP Investment in Green Roofing
Private Green Subsidies	Exogenous	US Dollars/Year	Annual Subsidies for Green Roofing Offered by Private Organizations
Standardized Green Incentives	Endogenous	US Dollars/Acre	Total Green Roofing Financial Incentives Offered Per Acre of New Roof Construction in a Given Year
Private Solar Subsidies	Exogenous	US Dollars/Year	Annual Subsidies for Solar PV/BIPV Roofing Offered by Private Organizations
Solar GDP Investment	Exogenous	DMNL[1]	Annual Net Fractional GDP Investment in Solar PV/BIPV Roofing
Standardized Solar Incentives	Endogenous	US Dollars/Acre	Total Solar PV/BIPV Roofing Financial Incentives Offered Per Unit of New Roof Construction in a Given Year
Standardized GRIPV Incentives	Endogenous	US Dollars/Acre	Total GRIPV Roofing Financial Incentives Offered Per Acre of New Roof Construction in a Given Year
Feasibility of Government Support	Endogenous	DMNL[1]	Total Remaining GDP Fraction After Investment in Financial Incentives

[1]Dimensionless

Table 16: Cost Effectiveness Parameters for Each Alternative[1]

Parameter Information	*Type*	*Units*	*Description*
Alternative Wastewater Savings	Endogenous	US Dollars	Total Yearly Contribution of Alternative Roof Type "i" to Savings on Wastewater Costs
Alternative Electric Utility Savings	Endogenous	US Dollars	Total Yearly Contribution of Alternative Roof Type "i" to Savings on Wastewater Costs
Alternative Operational Savings	Endogenous	US Dollars	Total Yearly Contribution of Alternative Roof Type "i" to Buildings' Operational Savings
Alternative Gross Investment Cost	Endogenous	US Dollars	Total Yearly Gross Investment Costs in Orlando for Alternative Roof Type "i"
Alternative Financial Incentives	Endogenous	US Dollars	Total Yearly Available Financial Incentives for Alternative Roof Type "i"
Standardized Alternative Incentives	Endogenous	US Dollars/Acre	Yearly Financial Incentives Available for Alternative Roof Type "i" Per Unit of Area Installed
Alternative SNV	Endogenous	US Dollars/Acre	Standardized Net Value of Alternative Roof Type "i" Per Unit of Area Installed
Conventional SNV	Endogenous	US Dollars/Acre	Standardized Net Value of Conventional Roofing Per Unit of Area Installed
Other AltRoof SNVs	Endogenous	US Dollars/Acre	Sum of the Standardized Net Values of Alternative Roofing Options Other Than Alternative Roof Type "i" Per Unit of Area Installed
Alternative Cost Effectiveness	Endogenous	DMNL[2]	Cost Effectiveness of Alternative Roof Type "i" Relative to Other Roofing Options

[1] These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.
[2]Dimensionless

Lastly, parameters corresponding to non-economic practical concerns (lifetimes, roof loads, and contractor experience) are summarized in Table 17. It must once again be noted that the same basic parameters and core causal structures in this regard will apply to all alternative roofing options, so for purposes of this CLD, one diagram will suffice for all three alternative roof types. Contractor experience is modeled as a single-inflow stock for each option, while lifetimes and loads are used to evaluate the "market impact" of a particular roofing option's usable lifetime and overall roof load, respectively; together, these three inputs will be used to evaluate the overall practicality of each roofing option relative to that of all other roof types. In order to ensure consistency in the model inputs, loads per unit area for each roof type will be calculated by multiplying its density by its thickness, and any required loads in addition to the load of the roof itself (vegetation, solar PV mounting, etc.) will also be included as applicable. For instance, most solar PV arrays today will also have additional mounting equipment to hold the panels in place at the proper angle, thus adding a slight extra load to the total added roof load for the solar panels; this additional load will be accounted for as an extra parameter in the sub-models for solar PV roof systems and GRIPV systems; in later analyses, this mounting load will be gradually reduced to zero in order to simulate the reduced need for mounting equipment as BIPV roofing becomes more prevalent. Likewise, although no data could be found on vegetation for green roofs, an additional parameter for vegetation loading can be added based on available guideline data for green roof vegetation (Francis et al. 2014). Lastly, although the units for these loads will use square feet instead of acres, the use of load ratios will nevertheless cancel out all units, so no unit conversion is necessary in this sub-model.

Table 17: Practical Parameters for Each Alternative[1]

Parameter Information	*Type*	*Units*	*Description*
Alternative Contractor Experience	Endogenous	DMNL[2]	Multiplier Representing Total Cumulative Practical Experience with Alternative Roof Type "i"
Alternative Contractor Learning	Endogenous	Per Year	Practical Learning Curve With Respect to Alternative Roof Type "i"
Alternative Contractor Training	Exogenous	DMNL[2]	Rate of Increase in Practical Experience with Alternative Roof Type "i"
Alternative Roof Lifetime	Endogenous	Years	Life Expectancy of Alternative Roof Type "i" Before Replacement is Needed
Conventional Roof Lifetime	Endogenous	Years	Life Expectancy of Conventional Roofing Before Replacement is Needed
Other AltRoof Lifetimes	Endogenous	Years	Sum of the Life Expectancies of Alternative Roofing Options Other Than Alternative Roof Type "i"
Market Impact of GRIPV Roof Lifetime	Endogenous	DMNL[2]	Multiplier Representing Comparison Between the Lifespan of Alternative Roof Type "i" & the Lifetimes of Other Roofing Options
Alternative Roof Density	Exogenous	kg/ft^3	Average Density of Alternative Roof Type "i"
Alternative Roof Thickness	Exogenous	ft	Overall Average Thickness of Alternative Roof Type "i"
Alternative Roof Additional Loads	Exogenous	kg/ft^2	Total Additional Loading Per Unit Area of Alternative Roof Type "i"
Alternative Roof Load	Endogenous	kg/ft^2	Total Roof Loading Per Unit Area of Alternative Roof Type "i"
Conventional Roof Load	Endogenous	kg/ft^2	Total Roof Loading Per Unit Area of Conventional Roofing
Other AltRoof Loads	Endogenous	kg/ft^2	Sum of Total Roof Loadings Per Unit Area of All Alternative Roofing Options Other Than Alternative Roof Type "i"
Market Impact of GRIPV Roof Loading	Endogenous	DMNL[2]	Multiplier Representing Comparison Between the Total Load of Alternative Roof Type "i" & the Total Loads of Other Roofing Options
Alternative Practicality	Endogenous	DMNL[2]	Multiplier Representing Overall Practical Feasibility of Alternative Roof Type "i"

[1] These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.
[2]Dimensionless

3.3 Causal Loop Diagram

Now that all of the applicable parameters for this study have been identified, the next step in this research is to draw a Causal Loop Diagram (CLD) for the system to be modeled. This CLD will serve as the primary conceptual framework from which to identify the key feedback loops within the overall system and properly develop the SD model as a valid representation of the modeled system in reality. Individual sub-model CLD diagrams are provided in Figures 16 through 25.

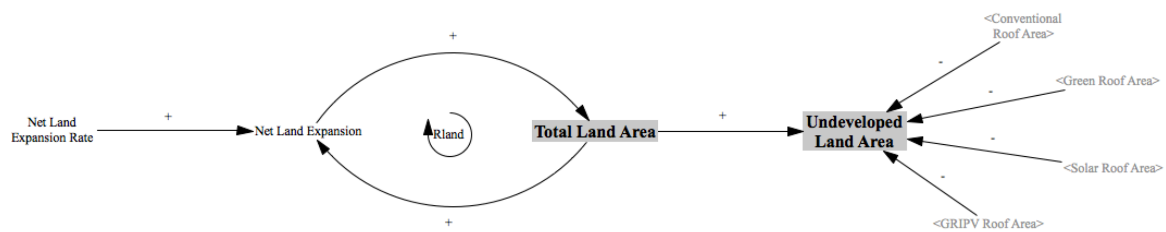


Figure 16: Land Area & Expansion CLD

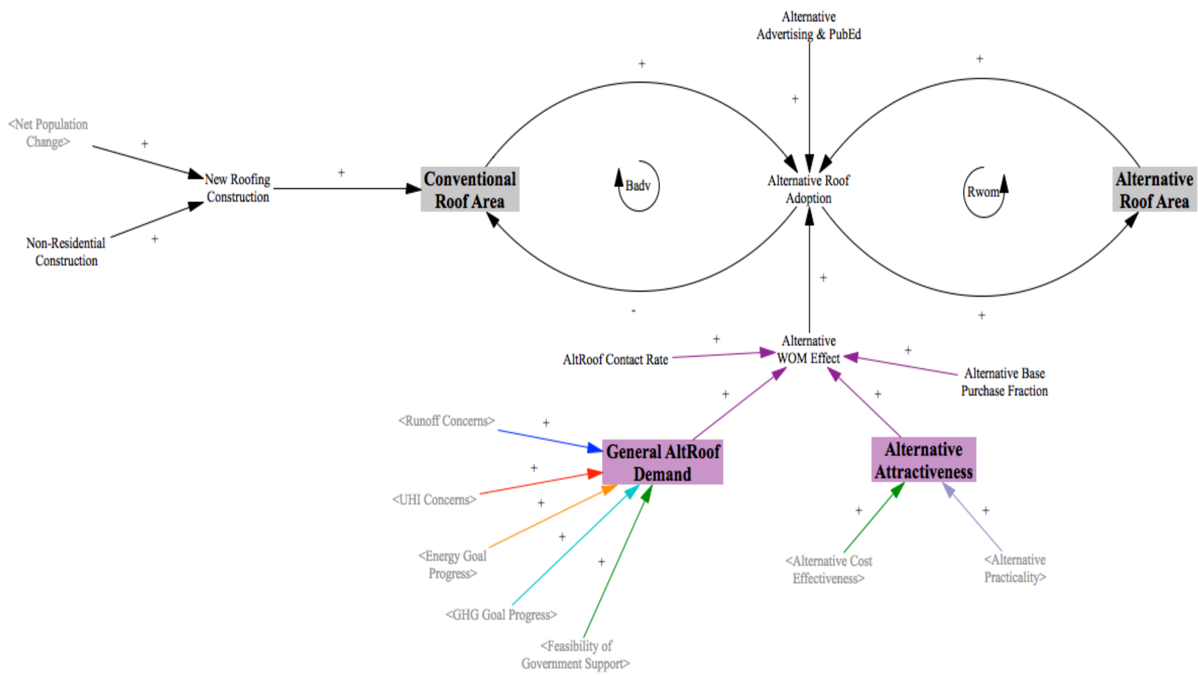


Figure 17: Main Diffusion CLD for Each Alternative Roofing Option

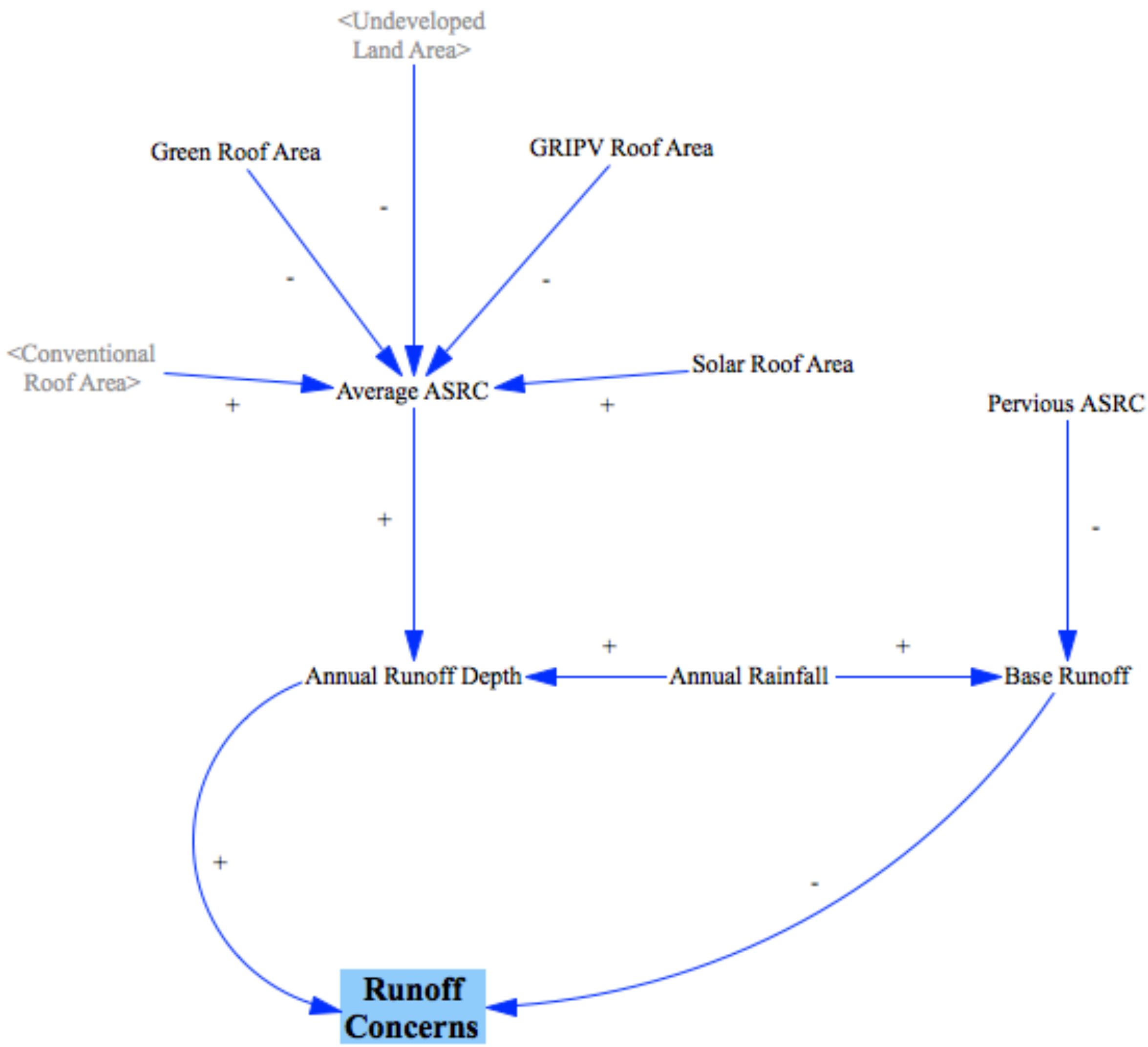


Figure 18: Urban Runoff CLD

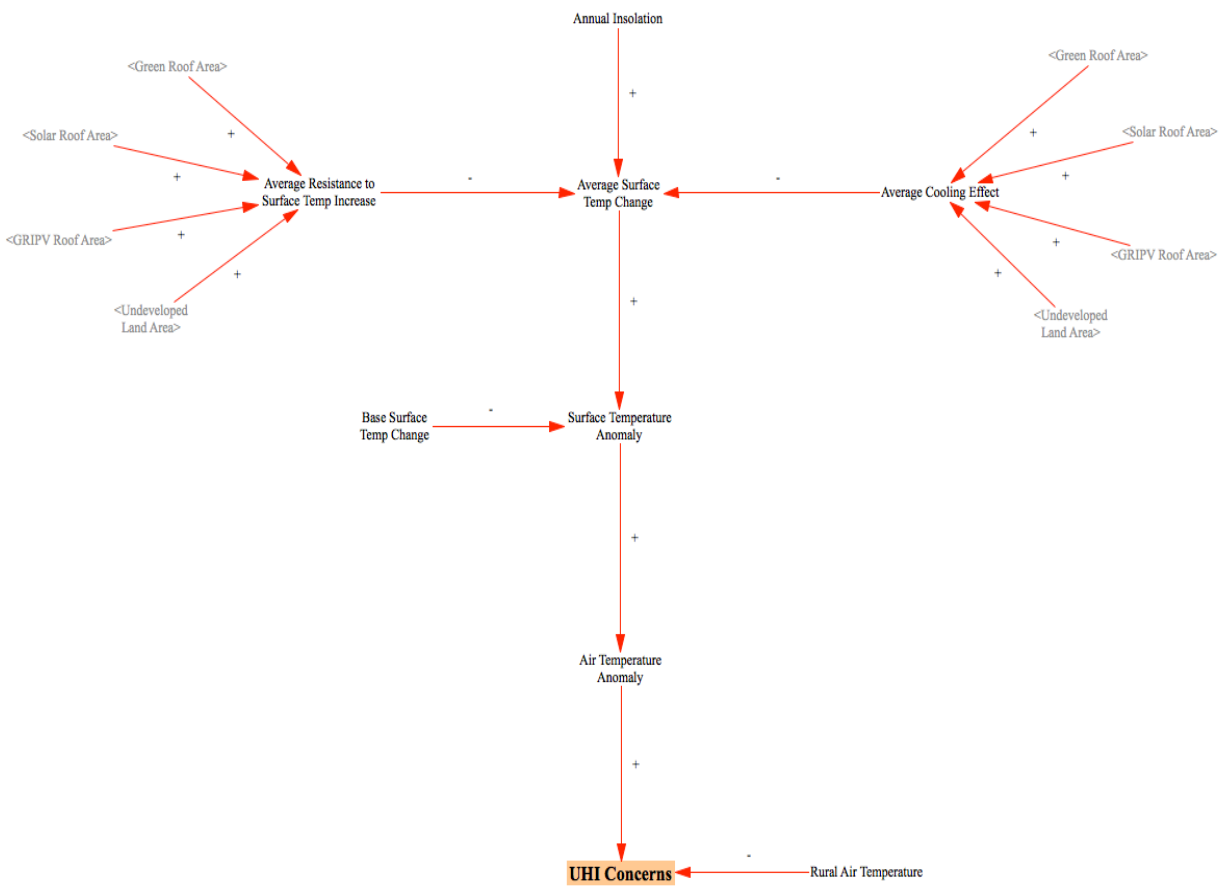


Figure 19: Urban Heat Island Effect CLD

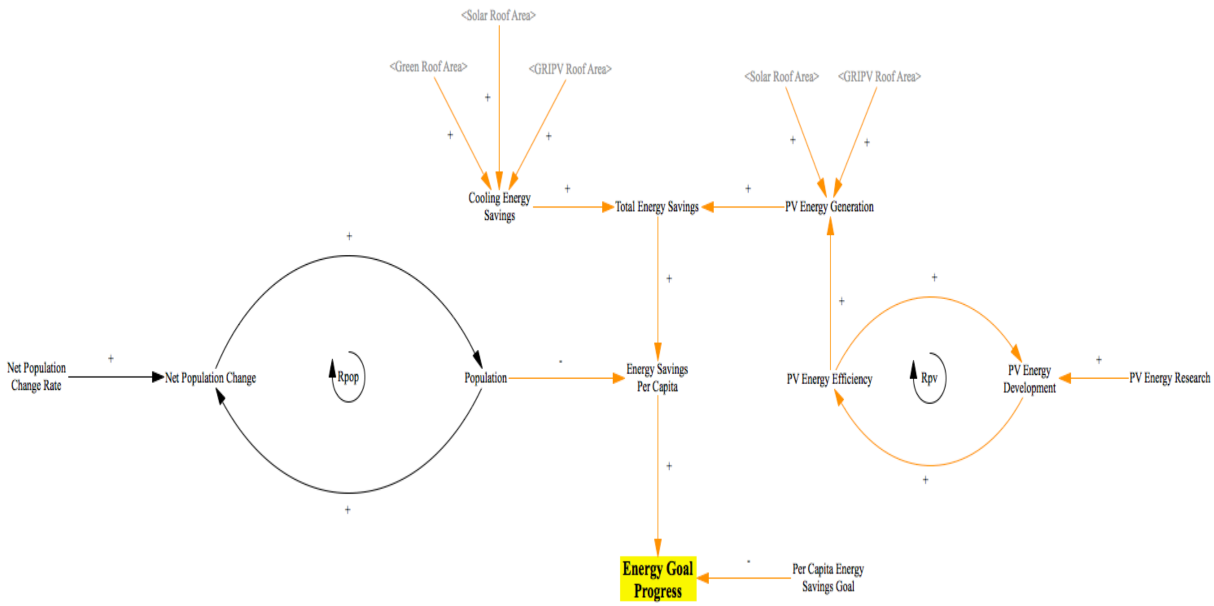


Figure 20: Population Growth & Energy Savings CLD

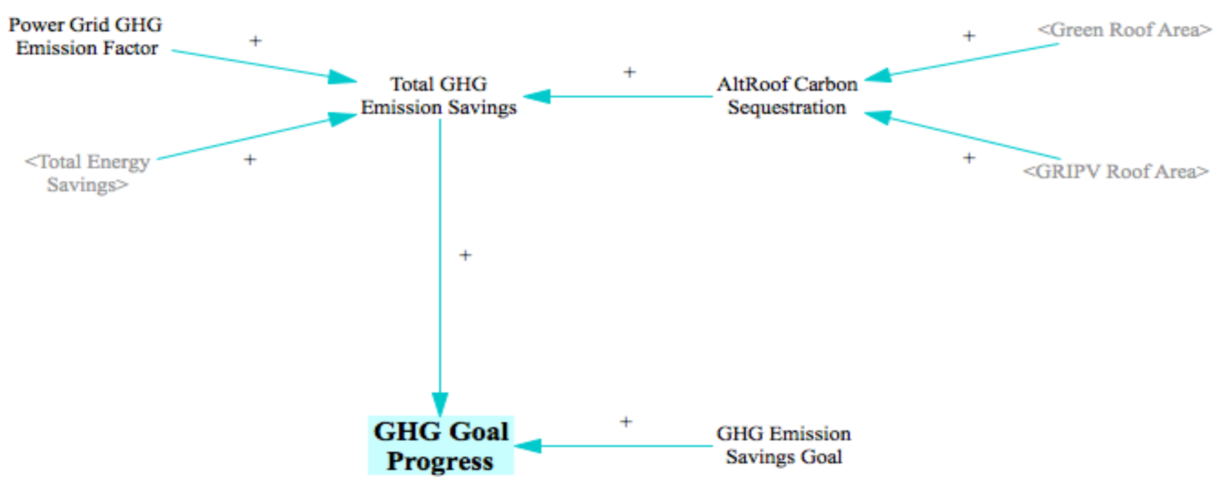


Figure 21: GHG Emission Savings CLD

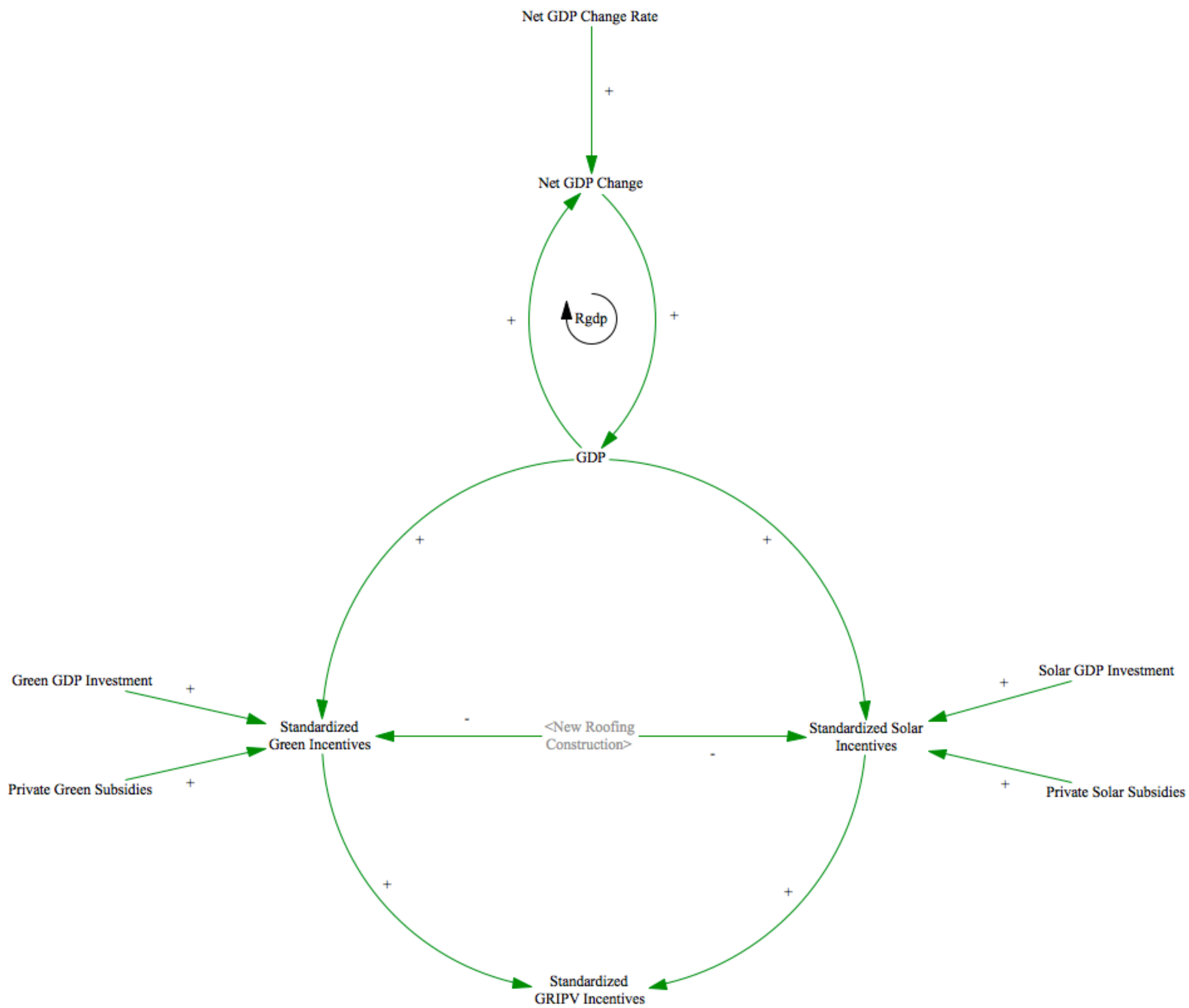


Figure 22: Financial Incentives CLD

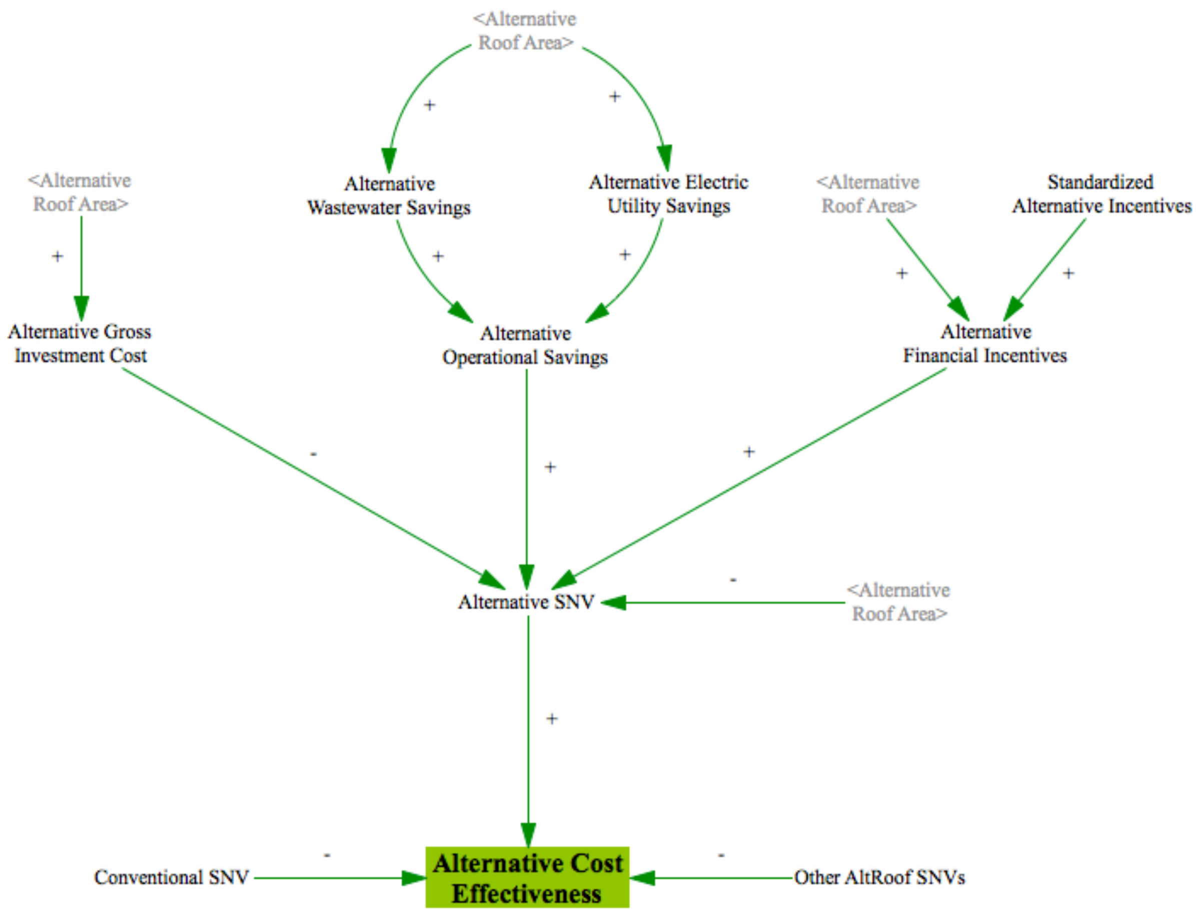


Figure 23: Cost Effectiveness CLD for Each Alternative Roofing Option

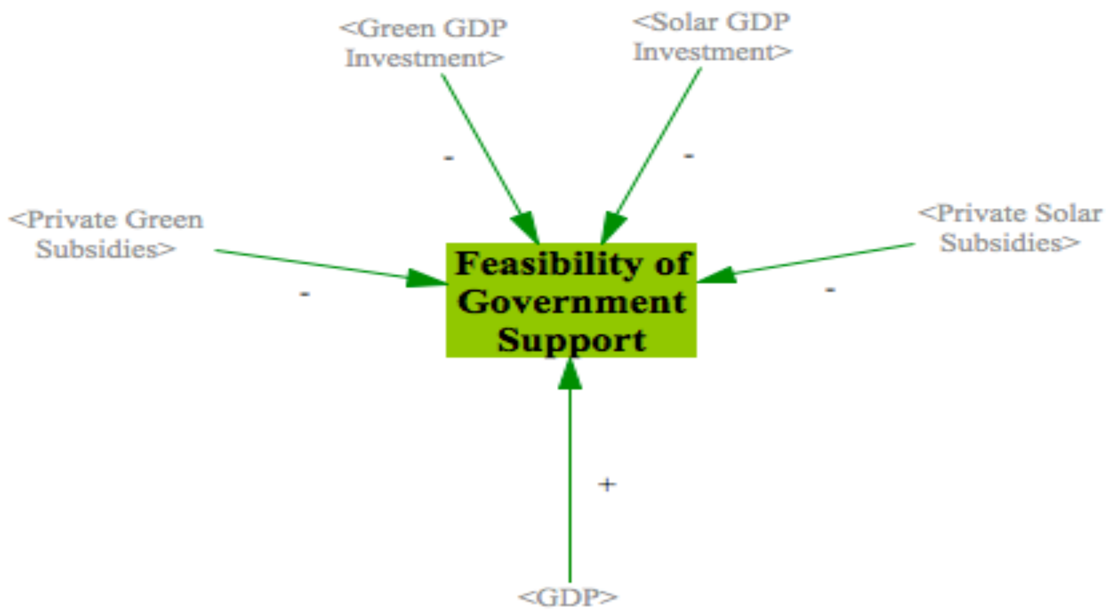


Figure 24: Overall Economic Feasibility CLD

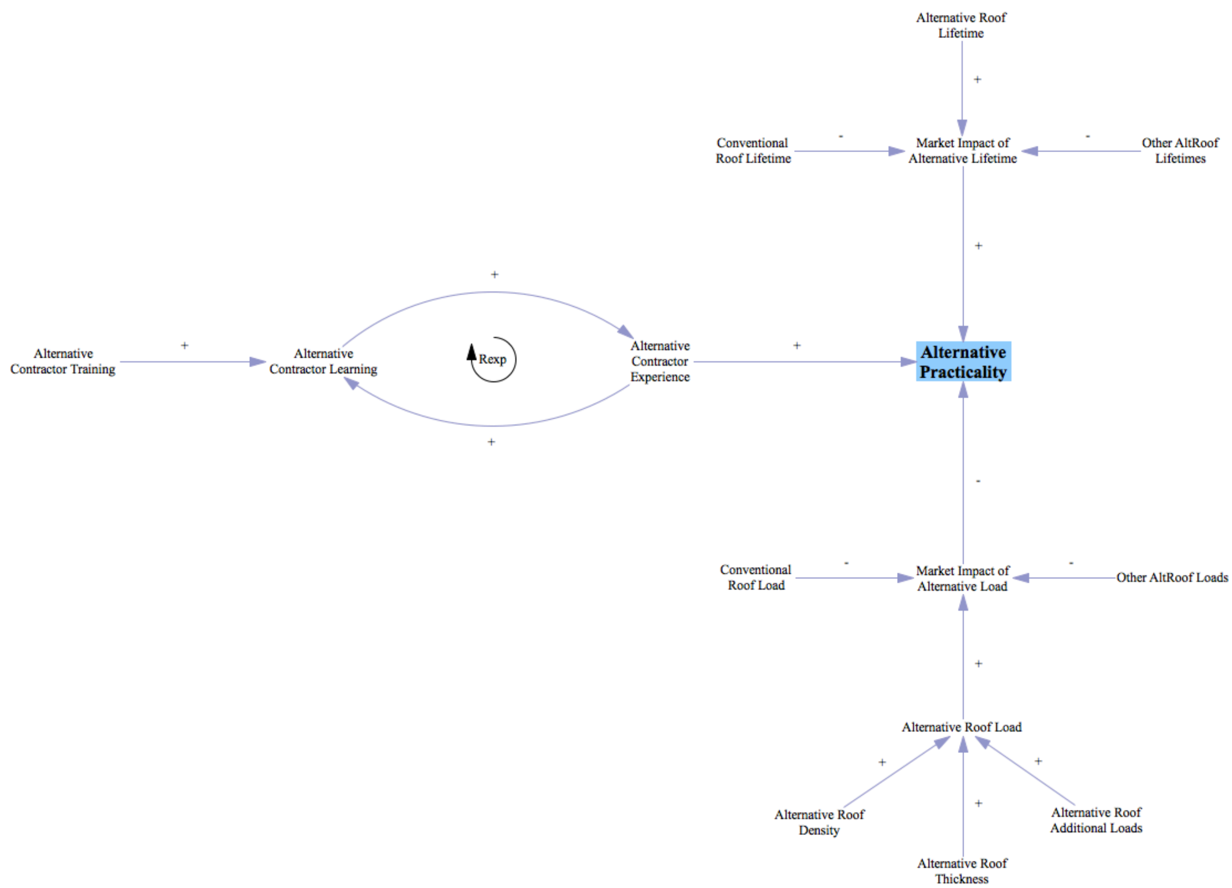


Figure 25: Practicality CLD for Each Alternative Roofing Option

The feedback loops in the CLD, as previously discussed, can fall under one of two distinct categories:

- *Positive ("Reinforcing") loops*, in which an increase in any one variable within the loop results in a subsequent additional increase in the same variable, and
- *Negative ("Balancing") loops*, in which an increase in any one variable within the loop results in a subsequent decrease in the same variable.

Note that, in order to avoid redundancy, some sub-model CLDs (Figures 17, 23, and 25) were illustrated with general diagrams that apply each alternative roofing option, because these sub-models have identical causal feedback structures for each alternative roofing option.

There were 6 positive/reinforcing feedback loops observed in the CLD diagrams illustrated earlier in this section, which are listed as follows:

- *LOOP "R_{Land}" (Figure 16)*

  A net increase in land expansion ("Net Land Expansion Rate" > 0) for the city of Orlando in any given year will increase the total available land area, including developed and undeveloped land area. This increased land area means that, if the net land expansion rate is unchanged, the net land expansion will be even greater in the following year.

- *LOOP "R_{WOM}" (Figure 17)*

  Any increase in the market share of any particular alternative roofing option ("Alternative Roof Area") will strengthen its corresponding word-of-mouth effect, in turn increasing its market penetration and future market shares.

- *LOOP "R_{Pop}" (Figure 20)*

  A net growth in population ("Net Population Change Rate" > 0) in any given year will increase the total population. This increased population means that, if the net population growth rate is unchanged, the net population growth will be even greater in the following year.

- *LOOP "R_{PV}" (Figure 20)*

  As research on solar energy (esp. solar PV electricity) progresses, the energy efficiency of solar PV/BIPV technologies will improve. If the improvement rate in solar PV efficiency remains the same for the following year, this will result in an even greater subsequent improvement in solar PV efficiency in the following year. Note that, since this feedback loop represents a learning curve, solar PV efficiency is assumed to never decrease ("PV Energy Research" ≥ 0).

- *LOOP "R_{GDP}" (Figure 20)*

  A net growth in the local GDP of Orlando ("Net GDP Change Rate" > 0) in any given year will increase the total GDP. This increased GDP means that, if the net GDP growth rate is unchanged, the net GDP growth will be even greater in the following year.

- *LOOP "R_{Exp}" (Figure 25)*

  As contractors learn more about a particular alternative roof type and its proper usage, they gain experience with said alternative roof type and how to properly install and maintain it, allowing future contractors to learn about and gain experience with this alternative roof type even more quickly. Note that, since this feedback loop represents a learning curve, this model will assume that contractor experience with any particular roofing option can never decrease (e.g. "Green Contractor Training" ≥ 0).

There was 1 negative/balancing feedback loop observed in the CLD diagrams illustrated earlier in this section:

- *LOOP "B_{Adv}" (Figure 17)*

  An increase in conventional roof development means that more conventionally developed area is available to be attracted via advertising and/or public education, resulting in an increase in the market penetration of all alternative roofing options to varying degrees, but also reducing the available conventionally developed area to be attracted in this manner in the future. Note that this study will assume that alternative roofing adoption only includes adoption by conventionally developed roofing areas.

Note that these are the feedback loops that are immediately visible from the CLD diagrams. Since the CLD has been split into multiple sub-models, not all of the potential feedback loops are immediately visible. However, the remaining feedback loops consist of several "redundant" feedback loops that pass through different variables but still have the same overall effect on the modeled system. For purposes of this dissertation, these redundant feedback relationships are briefly summarized below in terms of their overall influences on the system:

- *Environmental Impacts & Goal Criteria (Balancing):* As alternative roofing adoption increases, each of the relevant environmental concerns (urban runoff, the UHI effect, energy demand, and GHG emissions) will be addressed to varying degrees depending on the specific market penetration rates of each alternative roofing option and the impacts that said option(s) would help to address.

However, as environmental concerns are thusly reduced, the future demand for alternative roofing will likewise decrease.

- *Economic Attractiveness (Balancing):* Any change in costs, operational savings, and/or financial incentives that will result in an increase in the standardized net value (SNV) of a particular alternative roofing option will make it more cost effective and encourage its adoption to a greater extent. However, since this SNV value is calculated per unit area of roofing installed, the higher installed area of the roofing option in question will in turn decrease its SNV and, if no further economic savings and/or incentives are made or offered, this will result in a subsequent decrease in market penetration. Additionally, increasing the availability of non-operational financial incentives will become less and less economically feasible at higher investment levels, decreasing "Feasibility of Government Support" and reducing future market penetration rates as the required financial burden on the city of Orlando to support the same level of market growth increases.

Now that the structure of the modeled system and the qualitative feedback relationships among its relevant parameters have each been established, the next step in the SD modeling process is to integrate the CLD's conceptual framework into a quantitative model of the system as a whole. To accomplish this, a stock-flow diagram (SFD) is generated using applicable mathematical equations and numerical constants, and this SFD and its formulation are each discussed in more detail in Section 4.1 in the next chapter.

CHAPTER FOUR (4) :: MODEL DEVELOPMENT

4.1 SD Model Formulation

Now that the qualitative setup for the conceptual aspects of the SD model is complete, the next step in the SD modeling process is to quantify the established model framework in Vensim by mathematically formulating the parameters in the causal loop diagram in terms of their connections to and feedback relationships with other parameters. In this section, the calculation processes programmed into the SD model in Vensim will be briefly summarized and discussed with respect to the most important output(s) of each sub-model. More details on the formulas, constants, and time-series data used in the model will be discussed further in Appendix D.

4.1.1 Land Expansion Sub-Model

The total land area is modeled as a single-inflow stock, the initial value and the inflow rates of which are modeled based on historical land area data and projections for the city of Orlando (COEDD 2014). This total land area represents the overall carrying capacity for urban development in the city of Orlando, meaning that the amount of undeveloped land ("Undeveloped Land Area") that is still available for future development can be calculated as follows:

$$A_{Undev} = A_T - (A_{Conv} + A_{Green} + A_{Solar} + A_{GRIPV}) \tag{3}$$

Where "A_{Undev}" is the total undeveloped land area in acres, "A_T" is the total overall land area in acres, and "A_{Conv}", "A_{Green}", "A_{Solar}", and "A_{GRIPV}" are the total developed land areas for each roofing option being considered in this study (conventional, green, solar, and GRIPV roofing, respectively), all in acres.

4.1.2 Population Sub-Model & Main Diffusion Model

The total population is modeled as a single-inflow stock, the initial value and the inflow rates of which are modeled based on historical population data and projections for the city of Orlando (COEDD 2014). Any increase in the population will also increase the demand for more urban development, and this relationship is modeled using the following equation:

$$NC = \frac{(\Delta P)(A_{Roof})(NRC)}{(S_{HH})} \tag{4}$$

Where "NC" is the amount of new roofing construction (assumed to consist entirely of conventional roofing prior to alternative roofing adoption) in acres/year, "ΔP" is the annual change in the population in any given year in persons/year, "A_{Roof}" is the estimated average roof area of a residential building in acres/household, and "S_{HH}" is the average household size in persons/household. Non-residential development (schools, hospitals, etc.) is more difficult to estimate or predict due to its heavy dependence on community-related needs and factors that are beyond the scope of this study, so for purposes of this model, the dimensionless multiplier "NRC" is included in the equation above to represent the estimated total area required for residential and non-residential development (in acres) per unit area of the required area for residential development (also in acres) in any given year.

The remainder of the main diffusion model essentially consists of three separate Generalized Bass Models (GBMs), each simulating the adoption process of one of three alternative roofing options (Set "I", indexed on "i"):

- *Green roofs* (i = 1),
- *Roof-mounted solar PV systems* and/or *BIPV roofing systems* (i = 2), and
- *GRIPV roofing systems* (i = 3).

As such, with respect to the formulations previously discussed in Section 1.1.7.1, the stock "Conventional Roof Area" is used as the Potential Purchasers stock for all three of these GBMs, and three Purchasers stocks ("Green Roof Area", "Solar Roof Area", and "GRIPV Roof Area") are used to represent the cumulative adoption of each alternative roofing type. The adoption flows for each of these GBM follow the same general formulation, as shown below:

$$AR_i = Ad_i + WOM_i \tag{5}$$

Where "AR_i" is the total annual adoption rate for alternative roofing option "i" in acres/year, "Ad_i" is the rate of adoption due to advertising and/or public education for alternative roofing option "i" in acres/year, and "WOM_i" is the rate of adoption due to word of mouth for alternative roofing option "i" in acres/year. "Ad_i" and "WOM_i" each also have their own general formulas as shown below:

$$Ad_i = A_{Conv}E_i \tag{6}$$

$$WOM_i = (D)(CR_i)(BPF_i)(RA_i)\frac{(A_{Conv})(A_i)}{(A_{Conv} + A_i)} \tag{7}$$

Where "A_{Conv}" is the total conventional roof area in acres, "A_i" is the total roof area of alternative roofing option "i" in acres, "CR_i" is the annual contact rate ($Year^{-1}$) between conventional roof owners and owners of alternative roofing option "i" (assumed to be the same for all alternative roofing options), and "BPF_i" is the fraction of such contacts with respect to alternative roofing option "i" that result in a purchase of alternative roofing option "i" if no external factors are considered. "D" and "RA_i" are multipliers representing the general demand for alternative roofing and the attractiveness of alternative roofing option "i" relative to other roofing options, respectively; the formulations for both of these multipliers will be explained in more detail in Appendix D.

4.1.3 Urban Runoff Sub-Model

To estimate the total annual runoff depth from the city of Orlando, the average overall Annual Storm Runoff Coefficient ($ASRC_{Overall}$) from all developed and undeveloped surfaces in the study area (Set "J", indexed on "j") is estimated as follows:

$$ASRC_{Overall} = \frac{\sum_{j=1}^{5}\left((ASRC_j)(A_j)\right)}{\sum_{j=1}^{5}(A_j)} \tag{8}$$

Where "$ASRC_j$" is the ASRC of surface type "j" (conventional roofs, green roofs, solar roofs, GRIPV roofs, and undeveloped land) and "A_j" is the total area of surface type "j" in acres. Finally, by multiplying the value of $ASRC_{Overall}$ by the total annual rainfall depth (which is modeled and projected based on available historical data), the total annual runoff depth can be estimated as shown below:

$$Q = (P)(ASRC_{Overall}) \tag{9}$$

Where "P" is the annual rainfall depth in inches and "Q" is the actual annual runoff depth in inches. Next, a hypothetical "base runoff" from a purely undeveloped landscape (also in inches) is calculated as shown below for comparison purposes:

$$Q_0 = (P)(ASRC_P) \tag{10}$$

Where "$ASRC_P$" is the ASRC of pervious surfaces, the value of which has already been cited in Table 3 in Section 1.1.9.1. Finally, the actual runoff is divided by this base runoff to estimate the degree of public concern with regard to urban runoff, as shown below:

$$Runoff\ Concerns = \frac{Q}{Q_0} \tag{11}$$

The parameter "Runoff Concerns" will be used later to calculate the multiplier "D", which represents the overall general demand for alternative roofing.

4.1.4 Urban Heat Island Sub-Model

The total extent of the Urban Heat Island Effect will be calculated as the estimated anomaly in urban air temperatures in the city of Orlando relative to the corresponding rural air temperatures. In this sub-model, this air temperature anomaly is estimated based on the annual horizontal insolation in the Orlando area (see Table 4 in Section 1.1.9.1) and the physical properties of each of the developed and undeveloped surfaces being considered in this study. To this end, the calculation process used in this sub-model can be broken down into six general steps:

1. The "cooling effect" of each surface type is estimated as a fraction of the average horizontal insolation, based on the albedo of each surface type, as well as the cooling effects of vegetation on green roofs, GRIPV systems, and undeveloped land, as shown below:

$$CE_j = Alb_j + ET_j \tag{12}$$

Where "CE_j" is the overall cooling effect of surface type "j" as a fraction of horizontal insolation, "Alb_j" is the albedo of surface type "j", and "ET_j" is the cooling effect of the vegetation on surface type "j" as a fraction of horizontal insolation. This cooling fraction is used in the next to estimate on average how much of the annual horizontal insolation would be reflected and/or dissipated by a particular surface type, while the remainder is absorbed as heat and thereby contributes to the UHI effect.

2. The average change in surface temperature from nighttime to daytime is estimated for each surface type based on their respective cooling effects (CE_j), as well as their respective physical properties (thickness, density, and specific heat capacity). The equation used for this purpose is as follows:

$$STC_j = \frac{(I)\left(1 - CE_j\right)}{\left(t_j\right)\left(\rho_j\right)\left(s_j\right)} \tag{13}$$

Where "STC_j" is the night-to-day change in the surface temperature (in degrees Fahrenheit) of surface type "j", "I" is the average annual horizontal insolation in kWh/(ft^2*day), "CE_j" is the cooling effect of surface type "j" measured as a fraction of I, "t_j" is the thickness of surface type "j" in feet, "ρ_j" is the density of surface type "j" in kg/ft^3, and "s_j" is the specific heat capacity of surface type "j" in kWh/(kg*^{0}F).

3. Based on the night-to-day surface temperature changes and the total areas of each surface type, the average overall surface temperature change (in degrees Fahrenheit) for the city of Orlando as a whole is calculated as shown in the following formula:

$$STC_{Overall} = \frac{\sum_{j=1}^{5}\left(\left(STC_j\right)\left(A_j\right)\right)}{\sum_{j=1}^{5}\left(A_j\right)} \tag{14}$$

Where "STC_j" is the night-to-day change in the surface temperature (in degrees Fahrenheit) of surface type "j" and "A_j" is the total area of surface type "j" in acres.

4. The average surface temperature anomaly (STA) in the Orlando area (in degrees Fahrenheit) is calculated as follows:

$$STA = STC_{Overall} - STC_5 \qquad (15)$$

Where "$STC_{Overall}$" is the average overall surface temperature change (in degrees Fahrenheit) for the city of Orlando as a whole and "STC_5" is the night-to-day surface temperature change of undeveloped land surfaces, both in degrees Fahrenheit.

5. The air temperature anomaly (ATA) in urban areas in Orlando relative to rural areas is not as straightforward to calculate directly due to various external environmental factors (urban geometry, humidity, etc.) that are beyond the scope of this study. However, this air temperature anomaly can be estimated based on observed nationwide ranges in surface and air temperature anomalies from the U.S. Environmental Protection Agency (EPA 2008). Due to significant temporal and spatial variations (esp. in surface temperature), this surface-to-air ratio could range from as low as 0.417 to as much as 15 depending on the characteristics of a particular location, the time of day at which the temperatures are measured and compared, and various other factors as applicable. Due to a lack of available data

on surface temperatures and surface temperature anomalies in Orlando, the surface-to-air temperature anomaly ratio must be estimated within this range based on the historical data, after which the air temperature anomaly in the city of Orlando can be estimated as follows:

$$ATA = \frac{STA}{R_{S/A}} \tag{16}$$

Where "$R_{S/A}$" is the estimated surface-to-air temperature anomaly ratio ("STA/ATA").

6. After accounting for public perception delays in air temperature anomalies, the degree of public concern regarding the UHI effect is calculated as follows:

$$UHI\ Concerns = \frac{ATA_P}{T_{Rural}} \tag{17}$$

Where "ATA_P" is the publicly perceived air temperature anomaly (subject to a 3rd-Order, 2-year delay) and "T_{Rural}" is the average rural air temperature in the city of Orlando, both in degrees Fahrenheit. The parameter "UHI Concerns" will be used later to calculate the multiplier "D", which represents the overall general demand for alternative roofing.

The thickness, density, and specific heat capacity values of each of the four roof types considered in the model can all be easily derived from available literature data (Appendix D), but finding the corresponding values for undeveloped land surfaces is not so straightforward, primarily because the "thickness" and other relevant physical characteristics of undeveloped land in terms of measuring its absorption of the sun's heat is difficult to realistically assign a specific value due to several external factors (geothermal heat, potential variations in soil depth and composition, etc.) that are beyond the scope of this study. For purposes of this study, the "thickness" of undeveloped land is assumed to be equivalent to the *soil pedon depth* (i.e. the minimum depth of a particular soil type that contains the entire soil profile, typically used to estimate the total natural depth of the soil until the bedrock beneath it is reached) of Orlando Series soil from the National Cooperative Soil Survey (USDA 2001), and the values for undeveloped soil density and specific heat capacity are estimated based on the eight different soil types from Capozzoli et al.'s study (Capozzoli et al. 2013) in order to provide a sufficiently wide range of possible soil characteristics for inclusion in this study's uncertainty analyses.

4.1.5 Energy Sub-Model

To estimate the total energy savings from Orlando's alternative roofing market and its overall contribution to the energy targets and goals established for the city of Orlando (see Table 5 in Section 1.1.9.3), the energy savings from the individual markets of each alternative roofing option must first be calculated separately. For purposes of this study, the energy savings to be considered for each alternative roofing option will be divided into two primary categories:

1. The *reduction in the cooling energy load of a building* with each alternative roofing option relative to the cooling energy demand of a building with conventional roofing, calculated using the following general formula:

$$CL_i = (h_{Sun})(cl_i)(A_i) \tag{18}$$

Where "h_{Sun}" is the total number of annual sun hours in the city of Orlando in hours, "cl_i" is the cooling load reduction per unit area of alternative roofing type "i" in kW/acre, and "A_i" is the total area of alternative roofing type "i" in acres.

2. The *PV electricity generation* of each alternative roofing option (esp. the solar PV/BIPV and GRIPV roof options), calculated using the following general formula:

$$PV_i = (h_{Sun})(\eta_i)(p_i)(A_i) \tag{19}$$

Where "h_{Sun}" is the total number of annual sun hours in the city of Orlando in hours, "η_i" is the practical energy efficiency of the solar PV technology of alternative roofing type "i", "p_i" is the power capacity per unit area of the solar PV technology of alternative roofing type "i" in kW/acre, and "A_i" is the total area of alternative roofing type "i" in acres.

The individual and total energy savings can therefore be calculated using the following two equations:

$$E_i = CL_i + PV_i \tag{20}$$

$$E_{Overall} = \sum_{i=1}^{3} E_i \tag{21}$$

Where "CL_i" is the total cooling load reduction from alternative roofing type "i", "PV_i" is the total PV electricity generation from alternative roofing type "i" (assumed to be zero for green roofs), "E_i" is the total energy savings from alternative roofing type "i", and "$E_{Overall}$" is the total overall energy savings from the alternative roofing market as a whole, all in kWh. The average energy savings per capita can therefore be calculated as follows:

$$E_{pc} = \frac{E_{Overall}}{P} \tag{22}$$

Where "$E_{Overall}$" is the total overall energy savings in kWh and "P" is the total population in persons. Since the energy savings 2018 target and 2040 goal established for the city of Orlando are both measured on a per-capita basis, the value of "E_{pc}" can then be used to evaluate the overall contribution of Orlando's alternative roofing market to both of these established objectives, as shown in the following equations:

$$Energy\ Target\ Progress = \frac{E_{pc}}{\left(\left(E_{pc}\right)_{2010}(ERT)\right)} \tag{23}$$

$$Energy\ Goal\ Progress = \frac{E_{pc}}{\left(\left(E_{pc}\right)_{2010}(ERG)\right)} \tag{24}$$

Where "E_{pc}" is the average energy savings per capita in kWh/person, "$(E_{pc})_{2010}$" is Orlando's 2010 per-capita energy demand (used as the baseline for the energy reduction targets and goals) in kWh/person, "ERT" is the 2018 fractional reduction target in energy demand per capita relative to the baseline energy demand, and "ERG" is the 2040 fractional reduction goal in energy demand per capita relative to the baseline energy demand. "Energy Target Progress" and "Energy Goal Progress" will both be used later to calculate the multiplier "D", which represents the overall general demand for alternative roofing. Since both of these objectives were initially established in 2013 (Green Works Orlando 2016), STEP functions will be programmed into the model using Vensim such that "Energy Target Progress" will be the active parameter between the two from 2013 to 2018 to simulate the short-term (2018) energy savings target, while "Energy Goal Progress" will be the active parameter from 2018 to 2040 to simulate the long-term (2040) energy savings goal.

4.1.6 GHG Sub-Model

To estimate the total reduction in GHG emissions resulting from Orlando's alternative roofing market and the overall contribution to the GHG emission targets and goals established for the city of Orlando (see Table 6 in Section 1.1.9.4), the GHG emission savings must first be divided into two basic categories:

1. GHG emission savings due to *reduced energy demand*, and
2. GHG emission savings due to *carbon sequestration* by vegetated roof surfaces (green roofs and GRIPV systems).

Since the overall energy savings from the alternative roofing industry has already been calculated in the previous sub-model, it can technically be simply multiplied by Florida's regional emission factor (EPA 2014; EPA 2015) to yield the overall energy-related GHG emission savings; however, for purposes of this study, these GHG emission savings will be calculated individual for each alternative roofing option in order to more clearly demonstrate the overall GHG emission savings from each market. GHG emission savings from carbon sequestration must likewise be calculated individually based on carbon sequestration rates from the literature and (in the case of GRIPV systems) any potential growth in roofing vegetation that may have an impact on carbon sequestration potential. The equation used to calculate the GHG emission savings from each roof option can therefore be written as follows:

$$GHG_i = (EF)(E_i) + (cs_i)(A_i) \tag{25}$$

Where "EF" is the FRCC regional power grid GHG emission factor in metric tons of CO_2 per kWh, "E_i" is the total energy savings from alternative roofing type "i" in kWh, "cs_i" is the carbon sequestration rate for alternative roofing type "i" metric tons of CO_2 per acre, and "A_i" is the total area of alternative roofing type "i" in acres. The total overall GHG emission savings can then be compared to the GHG emission savings goal and target established for the city of Orlando (Green Works Orlando 2016) (which are already evaluated in terms of total overall emissions) as shown in the equations below:

$$GHG_{Overall} = \sum_{i=1}^{3} GHG_i \tag{26}$$

$$GHG\ Target\ Progress = \frac{GHG_{Overall}}{(GHG_{2007})(GRT)} \tag{27}$$

$$GHG\ Goal\ Progress = \frac{GHG_{Overall}}{(GHG_{2007})(GRG)} \tag{28}$$

Where “GHG_i” is the total GHG emission savings from alternative roofing type “i” metric tons of CO_2, “$GHG_{Overall}$” is the total overall GHG emission savings in metric tons of CO_2, “GHG_{2007}” is the total GHG emissions from the city of Orlando in 2007 (used as the baseline for the GHG emission reduction targets and goals), “GRT” is the 2018 fractional reduction target in GHG emissions relative to the baseline emission rate, and “ERG” is the 2040 fractional reduction goal in GHG emissions relative to the baseline emission rate. “GHG Target Progress” and “GHG Goal Progress” will both be used later to calculate the multiplier “D”, which represents the overall general demand for alternative roofing. Since both of these objectives were initially established in 2013 (Green Works Orlando 2016), STEP functions will be programmed into the model using Vensim such that “GHG Target Progress” will be the active parameter between the two from 2013 to 2018 to simulate the short-term (2018) GHG emission savings target, while “GHG Goal Progress” will be the active parameter from 2018 to 2040 to simulate the long-term (2040) GHG emission savings goal.

4.1.7 Economic Sub-Model

The economic sub-model deals with each of the key cost-related components of each roofing option. These components and how their applicable parameters are calculated are listed below as follows:

1. First, the *operational savings* for each alternative roofing option relative to conventional roofing can be divided into two basic categories:
   - Reductions in *wastewater costs* due to reduced urban runoff volumes, and
   - Reductions in *energy costs* due to the energy savings from the energy sub-model (Section 4.1.5).

   The operational savings can therefore be calculated for each alternative roofing option using the following general equations:

$$Q_i = (P)(ASRC_i) \qquad (29)$$

$$OS_i = (C_{WW})\left(27{,}154.3\,\frac{gal}{acre * in}\right)(Q_i)(A_i) + (LCOE_{Grid})(E_i) \qquad (30)$$

$$SOS_i = \frac{OS_i}{A_i} \qquad (31)$$

Where "OS_i" is the total operational savings for alternative roofing type "i" in US dollars, "SOS_i" is the standardized operational savings rate for alternative roofing type "i" in US dollars per acre, "P" is the total annual precipitation depth in inches, "$ASRC_i$" is the Annual Storm Runoff Coefficient for alternative roofing type "i", "Q_i" is the annual runoff depth from alternative roofing type "i" in inches, "C_{WW}" is the wastewater cost in US dollars per gallon, "A_i" is the total area of alternative roofing type "i" in acres, "$LCOE_{Grid}$" is the Levelized Cost of Electricity for the power grid in US dollars per kWh, and "E_i" is the total energy savings from alternative roofing type "i" in kWh.

2. Next, the *financial incentives* offered to each alternative roofing option are calculated using the following general equations with respect to green roofs and solar PV/BIPV roofing only (Set "K", indexed on "k"):

$$FI_k = (GDP)((IF_{GDP})_k) + (FI_{Sub})_k \quad (32)$$

$$SFI_k = \frac{FI_k}{NC} \quad (33)$$

Where "FI_k" is the total amount offered annually in financial incentives to alternative roofing type "k" in US dollars per year, "GDP" is Orlando's Gross Domestic Product in US dollars, "$(IF_{GDP})_k$" is the investment fraction of the GDP reserved for offering financial incentives for alternative roofing option "k", "$(FI_{Sub})_k$" is the sum of the additional subsidies being offered for alternative roofing type “k” in US dollars per year, “SFI_k” is the standardized amount of financial incentives available per unit area of alternative roofing type “k” in US dollars per acre, and “NC” is the total annual amount of new roofing construction in acres/year. Since GRIPV roof systems have only recently been introduced into the U.S. alternative roofing market and have not yet been introduced into or received any specific financial support from Orlando’s alternative roofing industry, it will be assumed for purposes of this study that the available standardized financial incentives for GRIPV systems (which are essentially integrated combinations of green roofs and solar PV technology) will already be included among the incentives offered separately for green roofs and for solar PV/BIPV roofing. As such, the available standardized financial incentives for GRIPV systems specifically are calculated using the following equation.

$$SFI_{GRIPV} = SFI_{Green} + (SC_{GRIPV})(SFI_{Solar}) \qquad (34)$$

Where “SC_{GRIPV}” is the fraction of GRIPV roof area that is covered with solar panels, and “SFI_{Green}” and “SFI_{Solar}” are the standardized financial incentives respectively offered for green roofs and solar PV/BIPV roofing, both in U.S. dollars per acre. In addition, the economic feasibility of the offered incentives for all alternative roofing options in any given year (“Feasibility of Government Support”) will be measured as a fraction of the GDP using the formula below:

$$FGS = 1 - \left(\left(\sum_{k=1}^{2} ((IF_{GDP})_k) \right) + \left(\frac{\left(\sum_{k=1}^{2} \left((FI_{Sub})_k * (1\ year) \right) \right)}{(GDP)} \right) \right) \qquad (35)$$

Where "$(IF_{GDP})_k$" is the investment fraction of the GDP reserved for offering financial incentives for alternative roofing option "k", "$(FI_{Sub})_k$" is the sum of the additional subsidies being offered for alternative roofing type "k" in US dollars per year, and "GDP" is Orlando's Gross Domestic Product in US dollars. It must be noted once again that this study will assume that the available financial incentives for GRIPV systems (which are essentially integrated combinations of green roofs and solar PV technology) will already be included among the incentives offered separately for green roofs and for solar PV/BIPV roofing. The value of "FGS" will be used later to calculate the multiplier "D", which represents the overall general demand for alternative roofing.

3. Third, now that the standardized operational savings and financial incentives for all alternative roofing options have been calculated, the standardized net values (SNVs) can be calculated for all alternative and conventional roofing options (Set "L", indexed on "l") based on their respective costs and all available savings and incentives, as shown below:

$$SNV_l = (SOS_l + SFI_l) - GC_l \qquad (36)$$

Where "SNV_l" is the standardized net value of roofing type "l", "SOS_l" is the standardized operational savings of roofing type "l", "SFI_l" is the standardized financial incentives offered for roofing type "l" in US dollars per acre, and "GC_l" is the gross cost (excluding savings and incentives) of roofing type "l", all in US dollars per acre. Note that operational savings are measured relative to conventional roofing operational costs and it is assumed that no financial incentives are offered for conventional roofing, so "SOS_l" and "SFI_l" are both equal to zero for conventional roofing, meaning that conventional roofing will always have a negative SNV.

4. Finally, now that the SNVs of all four roofing options have been calculated, the cost effectiveness of each alternative roofing option relative to all other roofing options can be calculated as follows:

$$CostEff_i = \frac{SNV_i}{\sum_{l=1}^{4} SNV_l} \tag{37}$$

Where "SNV_i" is the standardized net value of alternative roofing type "i" and "SNV_l" is the standardized net value of roofing type "l", both in US dollars per acre. The cost effectiveness of conventional roofing will not be included in this analysis because none of the adoption flows in the model flow into the "Conventional Roof Area" stock. The values of "$CostEff_i$" for each alternative roofing option will be used to calculate the multiplier "RA_i" for each alternative roofing option “i”, which represents the attractiveness of alternative roofing option “i” relative to all other roofing options.

4.1.8 Practical Sub-Model

The practical sub-model evaluates the non-environmental, non-economic practical usability of each alternative roofing option. More specifically, this sub-model analyzes the practicality of each alternative roofing option in terms of the following three factors:

1. The *usable lifetime* of each alternative roofing option,
2. The *load per unit area* of each alternative roofing option on a typical building, and
3. The *practical experience* of roofing designers and contractors with each alternative roofing option.

The first two of these factors (lifetime and load) are evaluated in terms of their “market impacts” with respect to each alternative roofing option, using the following two general equations:

$$\left(MI_{Life}\right)_i = \frac{L_i}{\sum_{l=1}^{4}(L_l)} \tag{38}$$

$$(MI_{Load})_i = \frac{\sigma_i}{\sum_{l=1}^{4}(\sigma_l)} \tag{39}$$

Where "L_i" is the usable lifetime of alternative roofing option "i" (excluding conventional roofing) and "L_l" is the usable lifetime of roofing option "l" (including conventional roofing), both in years. Likewise, "σ_i" is the roof load per unit area of alternative roofing option "i" (excluding conventional roofing) and "σ_l" is the roof load per unit area of roofing option "l" (including conventional roofing), both in kg/ft^2. Meanwhile, the practical contractor experience with respect to each alternative roofing option is modeled as three separate single-inflow stocks (one for each alternative roofing option) such that the overall practicality of each alternative roofing option can then be calculated as follows:

$$Prac_i = Exp_i * \left(MI_{Life}\right)_i * (MI_{Load})_i \qquad (40)$$

Where "Exp_i" is a dimensionless multiplier representing the cumulative practical experience with respect to alternative roofing option "i". The values of "$Prac_i$" will be used to calculate the multiplier "RA_i" for each alternative roofing option "i", which represents the attractiveness of alternative roofing option "i" relative to all other roofing options.

4.1.9 Attractiveness, Demand, & Word-of-Mouth Sub-Models

Now that all applicable environmental, economic, and practical parameters have been analyzed in each of the previous sub-models, the final step is to apply the findings from all of the previous sub-models in order to evaluate the general and specific demand levels for alternative roofing, which are each simulated in the following two multipliers:

1. The demand for alternative roofing in general ("D") is calculated as follows:

$$D = \frac{(Runoff\ Concerns)(UHI\ Concerns)(FGS)}{1 + (Energy\ Target\ Progress + Energy\ Goal\ Progress) + (GHG\ Target\ Progress + GHG\ Goal\ Progress)} \tag{41}$$

Where each of the parameters used in the above formula have already been calculated and discussed as shown in the previous sections, specifically in the runoff sub-model ("Runoff Concerns"), the UHI sub-model ("UHI Concerns"), the energy sub-model ("Energy Target/Goal Progress"), the GHG sub-model ("GHG Target/Goal Progress"), and the economic sub-model ("FGS").

2. The attractiveness of each alternative roofing option relative to all other available roofing options ("RA_i") is calculated as follows:

$$RA_i = (CostEff_i)(Prac_i) \tag{42}$$

Where each of the parameters used in the above formula have already been calculated and discussed as shown in the previous sections, specifically in the economic sub-model ("$CostEff_i$") and the practical sub-model ("$Prac_i$").

These multipliers are then applied to the word-of-mouth adoption rate for each alternative roofing option in any given year (see Section 4.1.2), and the cycle then repeats for the next simulation year. A more detailed explanation of the equations, constant values, and data sources used in the model will be provided in Appendix D. Now that this model has therefore been thoroughly formulated, the next step in the SD modeling process requires that the model be tested for its structural and behavioral validity, which will be discussed in the next section.

4.2 SD Model Validation

For a SD model to be considered valid for purposes of a particular research study, the structure and formulation of the model must be a reasonably accurate depiction of the modeled system in reality that accounts for all of the relevant factors needed for the analysis to be performed, and the model's behavior must adequately reflect how the modeled system would behave in reality. A number of structural and behavioral tests have been proposed in the literature to ensure the structural and behavioral validity of a particular model by analyzing its structure, formulation, and key model outputs (Barlas 1996; Shreckengost 1985). These tests will be discussed and summarized in the following two sections, and more details on the statistical analyses used for each test (esp. in behavioral tests) will be provided in Appendix E.

4.2.1 Structural Validation Tests

The structural validation tests used in this study and how they each apply to this model are listed and discussed below:

- The *structure verification test* directly evaluates the structure of the SD model by comparing it to the most up-to-date knowledge available on the modeled system in reality so as to confirm that the model is a reasonably accurate representation of the actual modeled system, especially with respect to the analyses to be performed. In other words, "every element of the model should have a real-world counterpart, and every important factor in the real system should be reflected in the model" (Shreckengost 1985). As previously discussed in Section 4.1, each sub-model was designed to represent a specific environmental, economic, practical, and/or societal aspect of Orlando's alternative roofing market and its subsequent impacts on the city of Orlando, with some sub-models being divided even further in order to account for as much of the relevant aspects of the modeled system as possible (e.g. costs, operational savings, and financial incentives in the economic sub-model). For this purpose, each individual sub-model's structure and formulation was specifically designed to reflect all applicable mathematical formulas and other relevant knowledge with respect to the specific area of focus that the sub-model was intended to represent. For instance, the runoff sub-model primarily focuses on calculating Orlando's average ASRC to determine the average annual runoff, the UHI sub-model evaluates solar insolation and the cooling effects of different roof surfaces, the energy sub-model evaluates cooling load reductions and PV efficiencies to estimate energy savings per capita, and the GHG sub-model uses these energy savings in conjunction with carbon sequestration from vegetated roofing to evaluate the resulting reduction in GHG emissions. All sub-models were thusly designed to reflect the actual calculation processes of all parameters that could be readily calculated mathematically, while any quantitative parameters that could not be as easily calculated were estimated based on available real-world data, and all qualitative parameters (e.g. contractor experience) were integrated into the model in such a way as to reflect their impacts on the modeled system despite them having no concrete mathematical formulas available from the literature for this purpose.

Therefore, it can be safely concluded that the model's structure adequately represents the structure of the modeled system in reality.

- The *parameter verification test* is similar to the structure verification test in that it compares the SD model to the modeled system in reality. Instead of the model's structure, however, the parameter verification test analyzes the model's parameters (esp. constant parameters) to ensure that they correspond "conceptually and numerically" (Barlas 1996) to their counterparts in the actual modeled system. As previously noted in Section 4.1, all of the numerically verifiable constants used in this model (e.g. green roof costs) were either directly derived from or estimated based on their corresponding real-world values from the literature (Appendix A & Appendix D), available case study data on real-world alternative roofing installations (Appendix C), and/or applicable historical data, as discussed in more detail in Appendix D (model formulation), in Appendix G (uncertainty analysis), and in Appendix H (case study policy & uncertainty analysis). Meanwhile, any and all constant parameters that could not be numerically measured (e.g. contractor training) were assigned values that would accurately reflect the degree to which they each impacted the modeled system in reality. Therefore, it can be safely concluded that the conceptual relationships and numerical values of all constant parameters adequately represent their real-world counterparts in the model.
- The *boundary adequacy test* is also similar to the structure verification test in that it analyzes the structure of the model. Instead of comparing the model's structure

to real-world knowledge of the system, however, the boundary adequacy test evaluates whether or not the structure and relationships within the model include all of the necessary details and parameters for the model to be able to adequately serve the purpose for which it was developed. In this study, the purpose of this model is to simulate Orlando's alternative roofing market and its resulting environmental and socio-economic impacts and to allow for thorough exploratory analyses to investigate how to best maximize the benefits typically associated with different forms of alternative roofing on a holistic long-term basis in the city of Orlando. For this purpose, in addition to the main diffusion model that simulates the alternative roofing market itself in terms of the adoption rates of different alternative roofing options, four separate environmental impacts (urban runoff, the UHI effect, energy demand, and GHG emissions) have been selected and modeled to simulate how the market penetration of alternative roofing options affects each of these environmental impacts on a long-term basis in the city of Orlando as a whole. In addition, as previously noted in Section 4.1, the economic and practical sub-models have been designed to account for as much of the relevant economic and practical aspects of the alternative roofing market as possible (operational savings, roof lifetimes, roof loads, contractor experience, etc.). Therefore, based on the most up-to-date available knowledge with respect to the modeled system in reality, it can be safely concluded that the boundary established in the model includes sufficient detail to simulate and analyze Orlando's alternative roofing industry as intended for this study.

- The *extreme conditions test*, as the name suggests, subjects the model to extreme conditions (e.g. setting advertising effectiveness equal to zero) in order to ensure that the model continues to behave as expected even when subjected to such extreme conditions. For example, if "Green Advert Effect" and the initial value of "Green Roof Area" are both set equal to zero at the beginning of the simulation, "Green Roof Area" should remain at zero throughout the entire simulation, because setting "Green Advert Effect" equal to zero means that no adoption can be encouraged via advertising, while setting "Green Roof Area" equal to zero means that there are no pre-existing green roof owners to encourage green roof adoption via the word-of-mouth effect. Likewise, in a GRIPV system, "GRIPV Solar Coverage" indicates the fraction of GRIPV area that is covered by solar panels, while "GRIPV Green Only Fraction" indicates the fraction of GRIPV area that is *not* covered by solar panels; therefore, "GRIPV Solar Coverage" and "GRIPV Green Only Fraction" must both be non-negative constants between 0 and 1 that must both add up to 1. In this model, as discussed in more detail in Appendix D, all possible extreme conditions that could be programmed into the model have been identified, and the formulation of the model has been adjusted to properly account for such extreme conditions. For example, the formula for "GRIPV Green Only Fraction" has been adjusted to include an IF THEN ELSE function as shown below:

$$GRIPV\ Green\ Only\ Fraction = IF\ THEN\ ELSE\begin{pmatrix} 0 \le GRIPV\ Solar\ Coverage \le 1, \\ 1-(GRIPV\ Solar\ Coverage), \\ NaN \end{pmatrix} \quad (43)$$

Where the value "NaN" in Vensim indicates an undefined or invalid numerical value, meaning that any data point with a "NaN" value is excluded from the simulation results.

- Lastly, the *dimensional consistency test* analyzes the mathematical equations within the model, confirming whether or not all of the units in the model equations are consistent in all of the model's equations without having to include "dummy" parameters that have no actual meaning in reality. For example, as previously shown in Section 4.1.7, the total operational savings from alternative roofing type "i" (in US dollars) is calculated as follows:

$$OS_i = (C_{WW})\left(27{,}154.3\,\frac{gal}{acre * in}\right)(Q_i)(A_i) + (LCOE_{Grid})(E_i) \quad (44)$$

Where "OS_i" is the total operational savings for the city of Orlando from alternative roofing type "i" in US dollars, "Q_i" is the annual runoff depth from alternative roofing type "i" in inches, "C_{WW}" is the wastewater cost in US dollars per gallon, "A_i" is the total area of alternative roofing type "i" in acres, "$LCOE_{Grid}$" is the Levelized Cost of Electricity for the power grid in US dollars per kWh, and "E_i" is the total energy savings from alternative roofing type "i" in kWh. The units for this equation (including the conversion from acre-inches to gallons) can therefore be broken down as follows:

$$(US\ Dollars) = \left(\frac{US\ Dollars}{gal}\right)\left(\frac{gal}{acre * in}\right)(in)(acre) + \left(\frac{US\ Dollars}{kWh}\right)(kWh) \qquad (45)$$

The units on the right-hand side all cancel out such that the final units of the equation are all in US dollars, meaning that the units in this equation are consistent. All other equations within the model have been evaluated in a similar manner, and all other units have been found to be consistent with no need to include unrealistic "dummy" parameters.

4.2.2 Behavioral Validation Tests

In general, behavioral validation tests analyze the behavior of key outputs in the model (e.g. "Total Runoff") to ensure that the model's behavior adequately reflects the behavior of the modeled system in reality. There are two separate types of behavioral validation tests that must be used in this study, each with respect to different outputs in the model:

- The *behavior reproduction test* directly compares the model's output during a given historical time period to a "reference mode" consisting of actual historical data on said output during the same time period. This test is preferable if sufficient historical data is available for use as a reference mode, because then the model output can be statistically compared to the reference mode data to test whether or not the model output and the reference mode are statistically similar. In this study, the statistical analyses used in the software StatPlus to compare each model output with its corresponding reference mode are summarized as follows:

- First, normality tests are run separately for the model output and for the reference mode, and an F-test is used to test whether or not the variances for both data sets are similar.
  - If both data sets pass both the normality tests and the F-test, the One-Way ANOVA Test can then be used to statistically compare the two data sets.
  - If either data set fails the normality tests and/or if the data sets fail the F-test, the Kruskal-Wallis Test must be used instead to statistically compare the two data sets.
- If the resulting significance value from either the One-Way ANOVA Test or the Kruskal-Wallis Test is greater than the desired confidence level (α = 0.05), then the data sets are confirmed to be statistically similar and therefore pass the behavior reproduction test. Otherwise, adjustments must be made to the model as needed until all data sets pass the behavior reproduction test.

For purposes of this study, sufficient historical data is available for use as reference modes for the following model outputs:

- Total Runoff
- Actual Air Temperature Anomaly

- Green Roof Area

- The *behavior reasonableness test* is used to determine whether or not the behavioral patterns of a particular model output match the corresponding behavior of the actual system to a reasonable degree. Unlike the behavior reproduction test, the behavior reasonableness test usually lacks a clear reference with which to compare the model output, and is therefore typically reserved for validating model outputs for which insufficient historical data is available for use as a reference mode. In this study, this test will be conducted in StatPlus by checking the model output for any possible outliers and accounting for other factors as applicable. Due to lack of sufficient reference mode data, the following model outputs must be tested using the behavior reasonableness test:
  - Solar Roof Area
  - GRIPV Roof Area
  - Energy Target/Goal Progress
  - GHG Target/Goal Progress

  Note that some of these model outputs (e.g. "GRIPV Roof Area") will not have any usable output during the validation period (1985 to 2013) with which to analyze their behaviors; for these parameters, the business-as-usual (BAU) or GRIPV-only (BAU+GRIPV) model outputs from 2013 to 2040 (See Section 5.1) will be used instead to determine the reasonableness of their behavior.

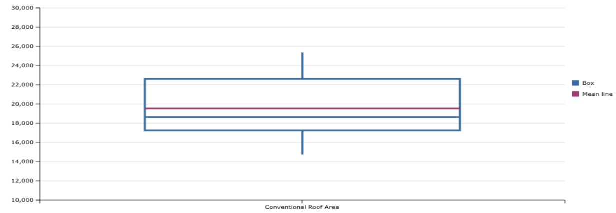
The normality test and F-test results for the behavior reproduction test, as well as more details on relevant results and details for both behavioral validity tests, will be presented and discussed in further detail in Appendix E. A brief summary of the final test results for the behavior reproduction test are summarized in Tables 18 and 19, and the outlier graphs for the behavior reasonableness test are presented in Figure 26. As indicated in Tables 18 and 19, the significance levels for the behavior reproduction test are all significantly higher than the required confidence level of 0.05, meaning that the model outputs for all three parameters are statistically similar to their respective reference modes. Moreover, in addition to all of the relevant considerations discussed in greater detail in Appendix E (e.g. the total installed solar PV capacity in 2013), no outliers were detected in any of the model outputs evaluated with the behavior reasonableness test, indicating that the behaviors of each of these outputs can be considered reasonable for purposes of this study given the lack of sufficient historical data for a direct statistical comparison.

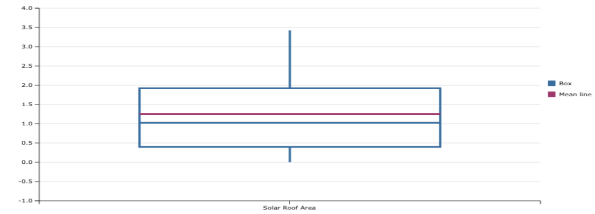
Table 18: Summary of One-Way ANOVA Test Results

Parameter	*F Statistic*	*Critical F Value*	*Significance*
Total Runoff	0.00853	4.01297	0.92673
Green Roof Area	0.1149	4.84434	0.74101

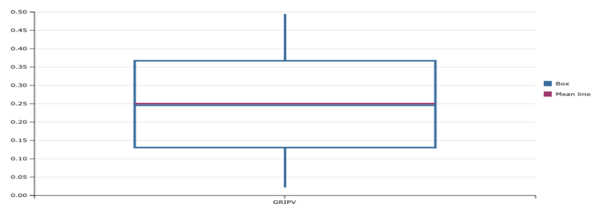
Table 19: Summary of Kruskal-Wallis Test Results

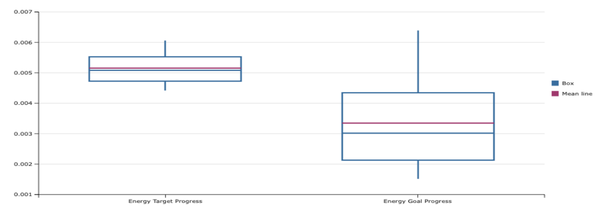
Parameter	*H Statistic*	*Corrected H Statistic*	*Significance*
Actual Air Temperature Anomaly	0.88521	0.88632	0.34678



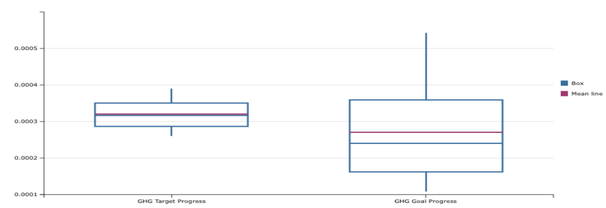


(a) (b)





(c) (d)



(e)

Figure 26: Outlier Graphs for Behavior Reasonableness Tests

(a) Conventional Roof Area (1985-2013)

(b) Solar Roof Area (1985-2013)

(c) GRIPV Roof Area (2021-2040 BAU+GRIPV Policy Scenario)

(d) Energy Target & Goal Progress (2013-2040 BAU Policy Scenario)

(e) GHG Target & Goal Progress (2013-2040 BAU Policy Scenario)

CHAPTER FIVE (5) :: EXPLORATORY ANALYSES

Now that the SD model for this study has been properly developed and validated, the model is ready to run simulations for the exploratory analyses to be performed in this study. These exploratory analyses can be generally categorized as follows:

- In *policy analyses*, one or more parts of the model are adjusted to simulate the implementation of various policy solutions in the modeled system. The resulting model outputs (typically for future time periods) are then analyzed and compared in order to draw reasonable conclusions about the potential effectiveness of the simulated policies in reality. For this purpose, these policy scenario results are usually also compared to a "business as usual" scenario in which the model is simulated for future time periods without any such adjustments.
- In *uncertainty analyses*, a full range of possible values for one or more different parameters (as opposed to the averaged or standard constant values originally programmed into the model) is tested in multiple simulation runs in order to evaluate the degree of uncertainty in the model results for future time periods. Unlike policy analyses, which evaluate the potential effectiveness of various policies and/or policy combinations, uncertainty analyses are used to evaluate the full range of possible future projections within the model based on all possible ranges and statistical distributions for various parameters, without the influence of any implemented policies. This allows for a more in-depth analysis of possible influencing factors that the policy scenarios in a policy analysis often cannot account for, which can sometimes in turn reveal areas within the modeled system

that may be targeted in future policy applications to develop a more robust and effective overall solution.

In this study, policies relating to investments in different types of alternative roofing and the introduction of GRIPV roofing into Orlando's alternative roofing market will be tested as part of a policy analysis (Section 5.1), and an uncertainty analysis will be used to evaluate possible ranges in all applicable parameters (roof costs, physical properties of different surfaces, etc.) to determine the degree of uncertainty as well as which areas might also be good targets for future development and/or policy applications (Section 5.2). A separate case study will also be conducted to analyze scenarios and possible probability distributions based on real-world policy applications (Section 5.3). The methodologies used in each of these analyses and the specific policies and ranges to be tested will be discussed in their corresponding sections, and the results of these analyses will be summarized and discussed in Chapter 6.

5.1 Policy Analysis

The primary goal of the policy analysis in this study is to simulate various degrees of investment in the Orlando markets of three different alternative roofing options (green, solar/BIPV, and GRIPV) and to analyze the resulting long-term impacts on the environmental impacts previously discussed in the city of Orlando as a whole. For green roofs and solar/BIPV roofing, these investments will be simulated as increases/improvements in the following aspects with respect to the green and/or solar roofing industries:

- Advertising and public education for prospective roof owners ("Advert Effect"),

- Financial incentives from the public and private sectors ("GDP Investment Rate" and "Private _____ Subsidies"), and
- Training for engineers and roofing contractors ("Contractor Training").

Since Orlando does not yet have any market penetration for GRIPV roofing, this study will also include the introduction of GRIPV systems into the alternative roofing market as a separate policy. Since GRIPV roofing is essentially an integration of green roofs and solar PV arrays, the following assumptions will be made in this regard:

- The effectiveness of advertising and public education with respect to GRIPV systems ("GRIPV Advert Effect") is proportional to the individual effectiveness levels for green roofs and solar PV/BIPV roofs ("Green Advert Effect" and "Solar Advert Effect", respectively),
- The standardized financial incentives (i.e. incentives offered per unit of roof area) available for GRIPV roofing ("Standardized GRIPV Incentives") are a function of the corresponding standardized incentives offered to green roofs and solar PV/BIPV roofs individually ("Standardized Green Incentives" and "Standardized Solar Incentives", respectively), and
- The rate at which contractors gain experience with GRIPV roofing ("GRIPV Contractor Training") is proportional to the corresponding training rates for green roofs and solar PV/BIPV roofs individually ("Green Contractor Training" and "Solar Contractor Training", respectively).

Qualitative summaries for each individual policy implementation (including policy activation years, investment levels to be tested, and brief descriptions) are provided in Table 20, and the general formulas used to simulate these policies are briefly summarized in Tables 21 and 22. Additional formulation (including the "policy switches" used to activate each policy) will be provided in Appendix F as needed. In this analysis, these policies will be tested individually and in different combinations in order to simulate and analyze all possible scenarios, and a "business as usual" scenario with no policy adjustments will also be simulated to serve as the primary basis for comparison with other scenarios. The results of this policy analysis will be summarized and discussed in Section 6.1.

Table 20: Descriptions of Policies to be Tested

Name	*Activation Year*	*Levels*[a]	*Affected Variable(s)*	*Description*
Green	2017	0, 1, 2	• Green Advert Effect • Green GDP Investment Rate • Private Green Subsidies • Green Contractor Training	Policy efforts are aimed at stimulating the green roof industry.
Solar	2017	0, 1, 2	• Solar Advert Effect • Solar GDP Investment Rate • Private Solar Subsidies • Solar Contractor Training	Policy efforts are aimed at stimulating the solar PV/BIPV roof industry.
GRIPV	2020	0, 1	• GRIPV Advert Effect	GRIPV roof systems are introduced into the alternative roofing market.

[a]Level 0 indicates no implementation of the corresponding policy (BAU conditions).

Table 21: General Policy Variable Formulas

Variable(s)	*Applied to Policies…*	*Formula(s)*
Green Advert Effect **Solar Advert Effect**	Green Solar	$Green\ Advert\ Effect = (1.0725\times10^{-6}) * (1 + Green\ Policy\ Level)$ $Solar\ Advert\ Effect = (2.691\times10^{-6}) * (1 + Solar\ Policy\ Level)$
Private Green Subsidies **Private Solar Subsidies**	Green Solar	$Private\ Subsidies = (1{,}000{,}000\ USD) * (Policy\ Level)$
Green Contractor Training **Solar Contractor Training**	Green Solar	$Green\ Contractor\ Training = (0.0012) * (1 + Green\ Policy\ Level)$ $Solar\ Contractor\ Training = (0.007) * (1 + Solar\ Policy\ Level)$
GRIPV Advert Effect	GRIPV	$GRIPV\ Advert\ Effect = \left(\frac{(Green\ Advert\ Effect) * (Solar\ Advert\ Effect)}{Green\ Advert\ Effect + Solar\ Advert\ Effect}\right) * (GRIPV\ Policy\ Level) * (1 + Green\ Policy\ Level + Solar\ Policy\ Level)$

Table 22: Lookup Inputs & Outputs for Green & Solar GDP Investment Rates

Policy Level (Lookup Input)	*GDP Investment Rate[a] (%) (Lookup Output)*
0	0.0%
1	10.3%
2	20.7%

[a]Based on Solar PV & renewable energy subsidy/incentive scenarios (IMF 2013; Jeon and Shin 2014)

5.2 Uncertainty Analysis

During the initial formulation of the SD model (Section 4.1), some of the parameters of the model were assigned constant values, most of which were the simple averages of applicable values from the literature. Although this formulation allows the model to simulate the most likely historical and future scenarios for the modeled system in reality, it fails to fully account for the inherent uncertainty and variability of these parameters and that of the modeled system as a whole. For example, according to the relevant literature (AMS 2016), the installed cost of a conventional roof can range from 4 USD/ft^2 to 6 USD/ft^2, so an average value of 5 USD/ft^2 was programmed into the model, thus simulating the model based on the average installed cost but failing to account for how the results might be affected if the actual installed cost were to be less than or greater than the average cost. As a result, although this initial formulation can still provide valuable insight in policy analyses (Section 5.1), it is unable to completely capture the full range of possible future projections. On the other hand, an uncertainty analysis can be used to simulate the full range of possible values for all constant parameters, as well as their associated probability distributions, thus allowing the model to simulate a full range of overall possibilities while also providing valuable insight into the likelihood of different scenarios. For this purpose, Vensim PLE Plus can program these probability distributions directly into the model for use in a Monte Carlo simulation, allowing Vensim to perform multiple simulations of the model, each with randomly selected constant parameter values based on their respective probability distributions.

A general summary of the parameters to be accounted for in this analysis is listed below:

- Annual green roof rainfall retention
- Albedos of different surface types
- Cooling load reductions from green roofs and solar PV/BIPV roofing
- Roof lifetimes
- Initial & annual costs of green roofs and conventional roofing
- Thicknesses, densities, & specific heats of green roofs, GRIPV green roof layers, and conventional roofing
- Density & specific heat of undeveloped soil
- Solar PV power capacity per acre

- Solar PV coverage on GRIPV roofing
- Percent increase in the solar PV power output of GRIPV roofs relative to that of standard solar PV/BIPV roof systems

A full detailed summary of all of the probability distributions to be used in the Monte Carlo simulation will be provided in Appendix G, and the results of this uncertainty analysis (with and without GRIPV market penetration) will be presented in Section 6.2.

5.3 Case Study Exploratory Analyses

To further enhance the exploratory analyses to be performed in this study, this model will also be applied to a case study of real-world alternative roofing policies, which will consist of the following exploratory analyses:

- An additional *policy analysis* testing the potential effectiveness of realistic policies that have been applied in the alternative roofing markets of different parts of the world (as opposed to the more theoretical policy analysis in Section 5.1), and
- An extension of the *uncertainty analysis* previously discussed in Section 5.2, which will account for all possible application ranges in the policies tested in this case study in addition to the parameter ranges previously accounted for in the original uncertainty analysis, thereby evaluating the overall level of uncertainty associated with the case study policies in this analysis when all possible external factors are considered.

Unlike the policy analysis of Section 5.1, in which different investment levels into all aspects of each individual alternative roofing option are tested to find an optimal distribution of such investments, this case study will directly analyze a number of past and current policies that have been or are being implemented in Orlando and in other parts of the world. Real-world examples of these policies with respect to both green roofs and alternative roofing in general include the following (Plant Connection, Inc. 2017; DOE 2017):

- Financial incentives for each alternative offered on a per-unit basis (per unit area for green roofing & per unit of electricity generated for solar roofing), and
- Bylaws requiring the installation of green roofing on newly constructed buildings (esp. industrial and commercial buildings) that meet certain criteria.

For purposes of the case study, the green roofing bylaws previously mentioned will also be applied to solar roofing and GRIPV roofing in order to analyze the potential responses of each individual market to such bylaws. Furthermore, since the applicability of solar energy in general and the resulting effectiveness of government support through financial incentives are both heavily dependent on regional climates and insolation rates, only solar PV incentives in the Central Florida area will be considered for the solar roofing incentives to be tested. Additional case study policies were also considered for inclusion in this case study analysis (e.g. enhanced public education and contractor training), but could not be included due to insufficient real-world data to realistically simulate their impacts on the alternative roofing market beyond what has already been simulated in the standard policy analysis (Section 5.1).

In order to apply the relevant policies to the model, some additional policy variables will be added to the model, and the values of other variables will be adjusted as necessary to reflect the policy to which they apply. A brief general formulation of the policies to be applied in this case study is presented in Tables 23 and 24, and a brief qualitative summary of the policy scenarios to be tested individually and in conjunction with each other will be provided in Tables 43 and 44. In addition, the following assumptions will be taken into account for purposes of this case study:

- The actual market penetration levels resulting from the implementation of alternative roofing bylaws will depend on a wide range of external factors beyond the scope of this study, including (but not limited to) the total roof area of individual buildings that meet the bylaw criteria, the minimum amount of coverage required on the building for the alternative roof to be installed, and whether the roof owner(s) in question will only install the bare minimum required alternative roofing area for a building to comply with the bylaws or are willing to adopt more than the bare minimum. Due to insufficient available data to properly model the impacts of each of these factors on the effectiveness of bylaw requirements on adoption rates, a “qualifying-area randomizer (QAR)” will be applied to each bylaw adoption rate to simulate the overall proportion of large non-residential development (100,000 ft^2 or larger) in a given year that will adopt an alternative roofing option under the applicable bylaws and bylaw requirements.
- Aside from the aforementioned randomizers, it will be assumed that the total bylaw adoption rate is proportionally distributed among all acceptable alternative roofing options under the specified bylaws. For instance, the “GRIPVBylaw” scenario (in which only GRIPV roofing is an acceptable option under the

established bylaws) will have only the "GRIPV Roof Bylaw Adoption Rate" parameter active, while the "AllThreeBylaw" scenario (in which all three alternative roofing options are acceptable under the established bylaws) will have all three "Bylaw Adoption Rate" parameters active with bylaw adoption rates distributed among all three alternatives.

- Since GRIPV systems are essentially a combination of green roofing and solar roofing, if GRIPV market penetration is taken into account and a bylaw is simulated that requires the adoption of green roofing and/or solar roofing, it will be assumed that GRIPV roofing is an acceptable alternative for purposes of the bylaw requirements and will therefore be adopted under said bylaw to some extent. In the model, this will be simulated as bylaw adoption rates being activated for GRIPV roofing in addition to the bylaw adoption rate(s) for the roofing alternatives covered in the bylaw (e.g. if a green roof bylaw is in effect and GRIPV market penetration is taken into account, the parameters "Green Roof Bylaw Adoption Rate" and "GRIPV Roof Bylaw Adoption Rate" are both activated).
- In scenarios where financial incentives are implemented in conjunction with the aforementioned bylaws, only the financial incentives corresponding to the specific alternative(s) allowed under the specified bylaw(s) will be implemented, thus simulating the use of financial incentives to support the bylaws in question. For instance, if bylaw adoption is required for green roofing but not for solar PV/BIPV roofing, only green roof financial incentives are implemented.

- It will be assumed that financial incentives for GRIPV systems are offered for their green and solar roofing components individually instead of being offered for the GRIPV system as a whole. Therefore, energy efficiency gains in GRIPV systems as opposed to standard solar PV/BIPV systems are not included in these incentive calculations.

More detailed conceptualization and formulations of the policy variables to be used in this case study will be presented in Appendix H as needed. The results of this case study (with and without the inclusion of GRIPV market penetration) will be presented and discussed in Section 6.3.

Table 23: General Case Study Policy Formulation

Parameter	*Units*	*Formula*	*Description*
Green Roof Bylaw Adoption Rate[a,b]	Acres/Year	$(New\ Roofing\ Construction) * \left(\frac{Non - Residential\ Construction}{1 + (Non - Residential\ Construction)}\right) * (RANDOMIZER)_i$	Bylaw-related green roof adoption.
Solar Roof Bylaw Adoption Rate[a,b]	Acres/Year	$(New\ Roofing\ Construction) * \left(\frac{Non - Residential\ Construction}{1 + (Non - Residential\ Construction)}\right) * (RANDOMIZER)_i$	Bylaw-related solar roof adoption.
GRIPV Roof Bylaw Adoption Rate[a,b]	Acres/Year	$(New\ Roofing\ Construction) * \left(\frac{Non - Residential\ Construction}{1 + (Non - Residential\ Construction)}\right) * (RANDOMIZER)_i$	Bylaw-related GRIPV roof adoption.
Case Study Green Incentives	USD/Year	$(Green\ Roof\ Incentives\ Per\ Acre) * \left(\frac{Green\ Roof\ Area + GRIPV\ Roof\ Area}{Green\ Roof\ Lifetime}\right)$	Total yearly amount of financial incentives offered for green roof installations on a per-acre basis.
Case Study Solar Incentives	USD/Year	$(Solar\ Roof\ Incentives\ Per\ kWh) * (Solar\ Power\ Capacity\ Per\ Acre) * (Annual\ Sun\ Hours) * (Solar\ PV\ Commercial\ Efficiency) * \left(\frac{Solar\ Roof\ Area + (GRIPV\ Roof\ Area)(GRIPV\ Solar\ Coverage)}{Solar\ Roof\ Lifetime}\right)$	Total yearly amount of financial incentives offered for solar PV/BIPV roofing installations on a per-kWh basis.

[a]Set "I" is the set of alternative roofing options, indexed on "i".

[b]Alternative roofing bylaw requirements do not specify how much of a particular roof must consist of green roofing, and the number of buildings with roofs that meet the bylaw criteria may vary due to factors beyond the scope of this study, so a dimensionless randomizer (See Table 24) has been included to simulate the final fraction of non-residential roofing construction that would require alternative roofing.

Table 24: Bylaw Adoption Randomizers for Alternative Roofing

Available Alternative Roofing Options[a]	*Randomizer Distribution Type*	*Minimum Value*	*Maximum Value*[b]
1	Uniform	0	1
2	Uniform	0	1/2
3	Uniform	0	1/3

[a]The number of options available under the bylaw requirements, depending on whether the policies in question only require alternative roofing and/or greener building materials in general (e.g. LEED certification requirements) or specifically require a certain type of alternative roofing (e.g. green roof bylaws in Toronto).
[b]In light of the assumptions previously noted, and in order to ensure that the sum of all bylaw adoption rates never exceeds the amount of new non-residential roofing construction in any given year, the maximum bylaw adoption rate for any individual alternative roofing option is assumed to be inversely proportional to the number of acceptable alternative roofing options under the specified bylaws, with values such that the maximum possible total never exceeds the total amount of non-residential roofing construction.

Table 25: Summary of Case Study Financial Incentive Policies

Financial Incentive Policy Scenario	*Units of Offered Financial Incentives*	*Average Value*[a,b]
GreenEco	USD Per Acre of Green Roofing	\$390,083.13/Acre (Approximately \$8.96/ft^2)
SolarEco	USD Per kWh of Solar PV Electricity Generation	\$0.09/kWh

[a](Plant Connection, Inc. 2017)
[b](DOE 2017)

Table 26: Summary of Alternative Roofing Bylaw Scenarios

Alternative Roofing Bylaw Policy Scenario	*Alternative Roofing Option(s) Available*	*Policy Description*
GreenBylaw	Green GRIPV[a]	New non-residential development must include some type of green roofing on at least some of its roof surface area.
SolarBylaw	Solar PV/BIPV GRIPV[a]	New non-residential development must include a roof-mounted solar PV array or BIPV system on at least some of its roof surface area.
BothBylaw	Green Solar PV/BIPV	New non-residential development must include some type of alternative roofing on at least some of its roof surface area, and GRIPV roofing systems are assumed to be unavailable as an alternative roofing option.
GRIPVBylaw	GRIPV	New non-residential development must include a GRIPV roofing system on at least some of its roof surface area.
AllThreeBylaw	Green Solar PV/BIPV GRIPV	New non-residential development must include some type of alternative roofing on at least some of its roof surface area, and GRIPV roofing systems are assumed to be available as an alternative roofing option.

[a]GRIPV roofing is available under this scenario if GRIPV market penetration is included.

CHAPTER SIX (6) :: RESULTS & DISCUSSION

The development of the SD model for this study is now complete, and the exploratory analyses to be performed in this study have been discussed and prepared, so now the final step is to run the specified simulations and analyze the results, from which appropriate conclusions can then be drawn with respect to the modeled system in reality. The outline for this chapter is as follows:

- First, the policy analysis results are presented and discussed in detail (Section 6.1);
- Second, the uncertainty analysis results are presented and discussed in detail (Section 6.2);
- Third, the case study policy and uncertainty analysis results are presented and discussed in detail (Section 6.3);
- Fourth, a final summary of the work performed in this study and the findings from Sections 6.1 through 6.3 is presented (Section 6.4);
- Fifth, the limitations of the methodologies and analyses used in this study are discussed in detail (Section 6.5);
- Finally, recommendations for future research on this topic are summarized and discussed (6.6).

Where necessary, additional figures, tables, and other details on the results from Sections 6.1 through 6.3 will be provided in Appendices I through K.

6.1 Policy Analysis Results

As previously noted in Section 5.1, the primary goal of the policy analysis in this study is to simulate various degrees of investment in the Orlando markets of three different alternative roofing options (green, solar/BIPV, and GRIPV) and to analyze the resulting long-term impacts on the environmental impacts previously discussed in the city of Orlando as a whole. For purposes of this section, the policy analysis results will be organized into one subsection for each output (except for, as listed below:

- Conventional Roof Area (Section 6.1.1)
- Green Roof Area (Section 6.1.2)
- Solar Roof Area (Section 6.1.3)
- GRIPV Roof Area (Section 6.1.4)
- Runoff Depth (Section 6.1.5)
- Air Temperature Anomaly (Section 6.1.6)
- Energy Goal Progress (Section 6.1.7)
- GHG Goal Progress (Section 6.1.8)

For easier reference, a summary of the policy scenarios with the best results for each output by the year 2040 is also presented in Table 27 below. These optimal results will all be discussed in more detail in each of their respective subsections.

Table 27: Summary of Optimal Policy Scenarios for Each Output

Output Variable	*Optimal Policy Scenario(s)*	*Best Year 2040 Value*	*Change v.s. 2040 Business as Usual Value*	*Change v.s. 2040 GRIPV Only Value*
Conventional Roof Area	Solar2+GRIPV	32,884 acres	-0.172%	-0.165%
Green Roof Area	Green2 Green2+GRIPV	2.9 acres	+149%	+148%
Solar Roof Area	Solar2	74.7 acres	+282%	+252%
GRIPV Roof Area	Green2+Solar2+GRIPV	7.3 acres	N/A[a]	+1,383%
Total Runoff	Green2+Solar2+GRIPV	18.7078 inches	-0.01%	-0.009%
Actual Air Temperature Anomaly	Solar2+GRIPV	+1.14678^{0}F	-0.098%	-0.096%
Energy Goal Progress	Solar2+GRIPV	4.13% of goal met	+546%	+488%
GHG Goal Progress	Solar2 Solar2+GRIPV	0.35% of goal met	+545%	+487%

[a]The BAU scenario does not include GRIPV market penetration.

6.1.1 Conventional Roof Area

The policy results with respect to conventional roof area will not be presented graphically in this section because the resulting graphs displayed no visible change in the air temperature anomaly in any scenario; instead, the graphical results will be included in Figures I1 and I2. The policy scenario with the best numerical results for air temperature anomaly is the "Solar2+GRIPV" scenarios, owing primarily to the relative maturity of the solar roof market compared to the green and GRIPV roof markets, allowing it to achieve higher levels of market penetration. Furthermore, as shown in Table 27, even the smallest possible total conventional roof area in 2040 (32,884 acres) is far greater than the largest possible area of any given alternative in the same year (up to 74.7 acres). Not only do these findings clearly demonstrate the predominance of conventional roofing in Orlando, but they also highlight the relative ineffectiveness of using conventional adoption strategies alone (i.e. retrofitting pre-existing conventional urban development with an alternative roofing option), since all newly constructed roofing in this policy analysis was assumed to initially consist of conventional roofing. In other words, it will also be crucial to develop alternative roof adoption strategies for new construction as well (e.g. the roofing bylaw policies in Section 5.3) and/or find ways to slow down the current growth trends in urbanization.

Policies aimed at reducing growing urbanization demand levels were beyond the scope of this study), but although urban construction and development in Orlando will inevitably increase to some extent as the population increases and (to a greater extent) as demand for non-residential development (schools, hospitals, office buildings, etc.) also increases, this demand can be reduced or at least offset by finding ways to use pre-existing land development more efficiently and thus reducing the need for new construction in the first place; in the SD model developed in this study, this would correspond to reducing "New Roofing Construction", which is the sole inflow into the "Conventional Roof Area" stock. Not all possible ways to reduce this net demand for new construction may be realistically feasible (e.g. demolishing occupied homes and/or other important buildings and landmarks to return the land to its natural state), but other reduction strategies may be available that can still be highly effective if properly implemented, such as renovating or rebuilding old construction instead of clearing undeveloped land space for new construction, as well as developing and adjusting socioeconomic systems to reduce the required land footprint for certain types of buildings (e.g. opportunities to work and/or study at home can reduce the required land space for office buildings and schools, respectively).

6.1.2 Green Roof Area

The policy results with respect to green roof area are presented graphically in Figure 27. As shown in these graphs, green roof market penetration is understandably at its highest when a high level of investment in green roofing is applied with no investments in solar roofing. However, it is interesting to note that, despite the market penetration of green roofing being significantly lower than that of solar roofing and marginal compared to conventional roof area (Figures I1 and I2), the green roof market was found to be surprisingly resistant to decreases in market penetration when investments in other roofing alternatives were applied to the model. For example, the 2040 green roof area under the Solar2+GRIPV scenario (no investment in green roofing and maximum investment in other alternative roof types) only decreased by 0.06 acres compared to the 2040 BAU green roof area (1.1 acres versus 1.16 acres). Consequently, although it is clear that Orlando's green roofing industry can benefit greatly from economic, educational, and technological policy initiatives, investments in other alternative roofing options would have a relatively minor impact on green roof market penetration, allowing for more diverse investment policies in the alternative roofing market as a whole. However, it must still be noted that green roof market penetration is still significantly lower than solar roof market penetration (Section 6.1.2) and is even smaller compared to the total conventional roof area (Figures I1 and I2), indicating that further development and policy applications will be needed to enhance green roof market penetration to a more significant degree and thus have a more substantial influence on the environmental impacts to be discussed in Sections 6.1.5 through 6.1.8.

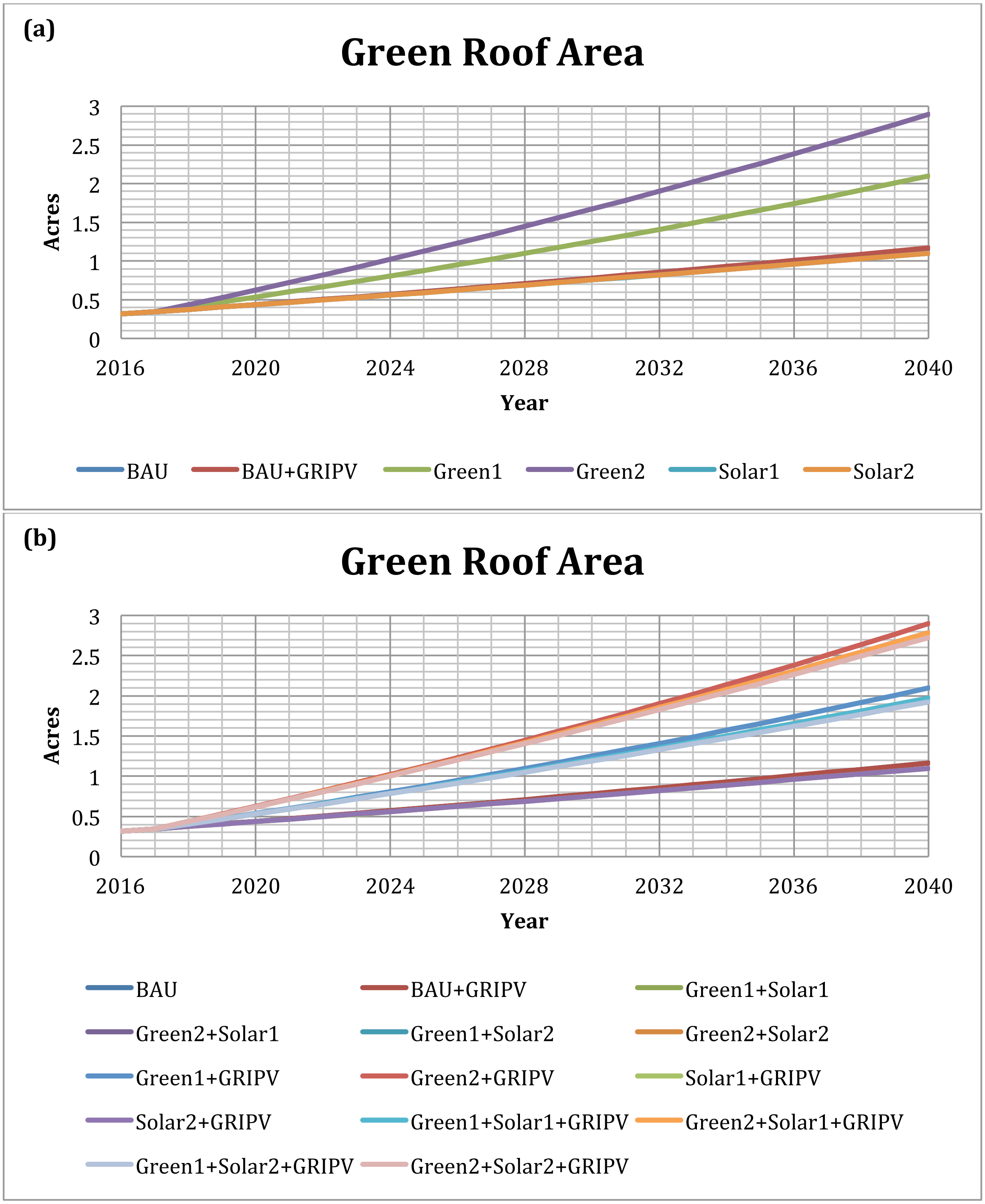


Figure 27: Green Roof Area Policy Results

(a) Individual Policies (b) Multiple Policies

6.1.3 Solar Roof Area

The policy results with respect to solar PV/BIPV roof area are presented graphically in Figure 28. Unlike the green roof market, which experienced very little adverse impact from investments in the solar roofing industry, the solar roof market was found to be significantly more sensitive to investments in the green roofing industry, resulting in a decrease in 2040 solar roof area of approximately 13 acres under the Green2+GRIPV scenario (no investment in solar roofing and maximum investment in other alternative roof types) compared to the BAU scenario (6.43 acres versus 19.55 acres). However, the solar roof market still maintains the highest penetration levels out of all three alternative roofing options in all scenarios, owing largely to the fact that the U.S. solar energy market as a whole (including solar roofing) has been continuously advancing and developing over several decades, as opposed to the relatively newer U.S. green roof market and the virtually nonexistent U.S. GRIPV market. Furthermore, just like how green roof market penetration increased significantly with more policy focus in the green roofing industry, the solar roofing market experienced significant growth when policy efforts focused on solar roofing investments, especially when policy efforts for other roofing alternatives were not included, although there was little difference when the solar roof policy level was changed from Solar1 to Solar2 in any given scenario. It is also worth noting that, in scenarios where investments in all three alternative roofing options were included, the resulting decreases in solar roof market penetration were not as drastic as when only green roof investments were applied, with some scenarios (e.g. the "Green2+Solar2+GRIPV" scenario) having 2040 solar roof areas that were only about 1.1 acres less than that of the BAU scenario. In other words, despite its greater sensitivity to investments in green roofing, the solar roof market still demonstrates enough flexibility to be able to find a reasonable balance for the market penetration levels of all alternative roofing options. Lastly, however, it must be noted that the market penetration of solar roofing in Orlando is still very small compared to the dominant market shares of conventional roofing, which may affect their overall environmental performance levels in the city of Orlando as a whole, as will be discussed in greater detail in Sections 6.1.5 through 6.1.8.

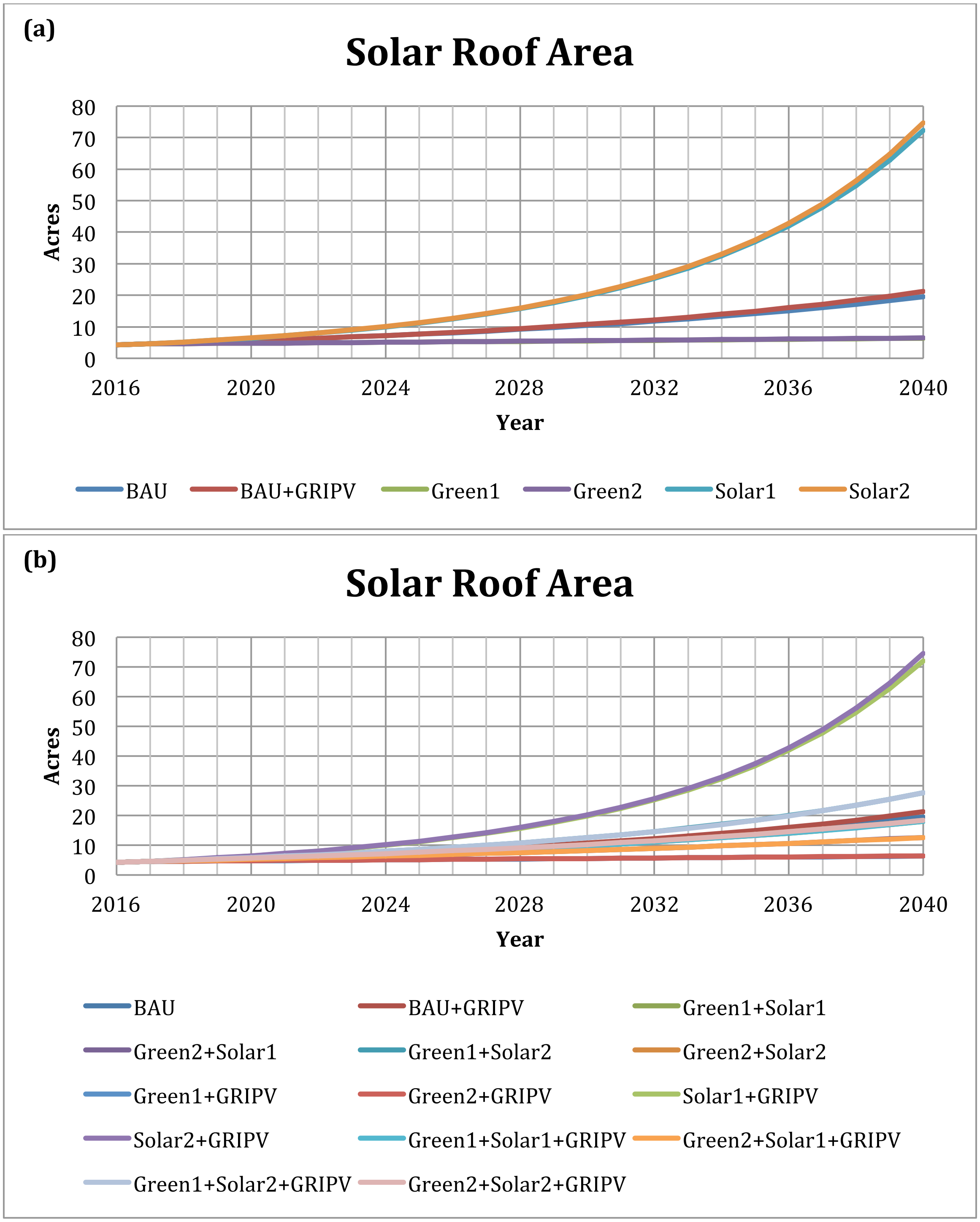


Figure 28: Solar Roof Area Policy Results

(a) Individual Policies (b) Multiple Policies

6.1.4 GRIPV Roof Area

The policy results with respect to GRIPV roof area are presented graphically in Figure 29. As previously noted, GRIPV roofs have only recently been introduced into the U.S. commercial market, and there is currently zero GRIPV market penetration in Orlando, so it must be noted that the GRIPV market penetration rates illustrated in these results are based on functions of parameters associated with green roofing and solar PV/BIPV roofing individually. Additionally, since the introduction of GRIPV systems into Orlando's alternative roofing market was implemented as a policy in and of itself, only policy scenarios that include the introduction of the GRIPV market will have any results for GRIPV market penetration.

That said, the results in Figure 29 indicate that, despite the 2040 GRIPV market penetration being consistently less than those of green and/or solar roofing (especially without additional policy investments), the 2040 GRIPV roof area managed to reach 41.4% of the corresponding market penetration of green roofing under the GRIPV-only policy scenario (0.48 acres versus 1.166 acres). Furthermore, GRIPV market shares were found to benefit greatly from investments into both green roofing and solar roofing with no evident reductions in market penetration (relative to the BAU+GRIPV scenario) from added investments in either green roofing or solar roofing, which is understandable because GRIPV roof systems are essentially a combination of green roofs and solar PV/BIPV arrays. At the highest possible investment level into the alternative roofing industry (the "Green2+Solar2+GRIPV" scenario), GRIPV roof area reaches a 2040 peak value of 7.3 acres (almost 15 times as much as the corresponding BAU+GRIPV acreage in 2040), surpassing the corresponding green roof area in the same scenario to make GRIPV systems the second most popular alternative roofing option after solar roofing. Lastly, it is worth noting that the results for GRIPV roofing generally tend to follow a trend most similar to the corresponding results for green roofing, meaning that market conditions in the green roofing industry can have a particularly strong influence on the GRIPV market.

These results, in short, clearly highlight that the GRIPV roof market has a great deal of potential in Orlando, especially as the green roofing and solar PV/BIPV industries both continue to make significant progress in terms of public education, financial support, and technological development. However, despite this potential, GRIPV market shares are still projected to be marginal compared to those of conventional roofing (Figures I1 and I2), thus drastically limiting the positive impacts of the GRIPV industry on the environmental categories to be discussed in Sections 6.1.5 through 6.1.8.

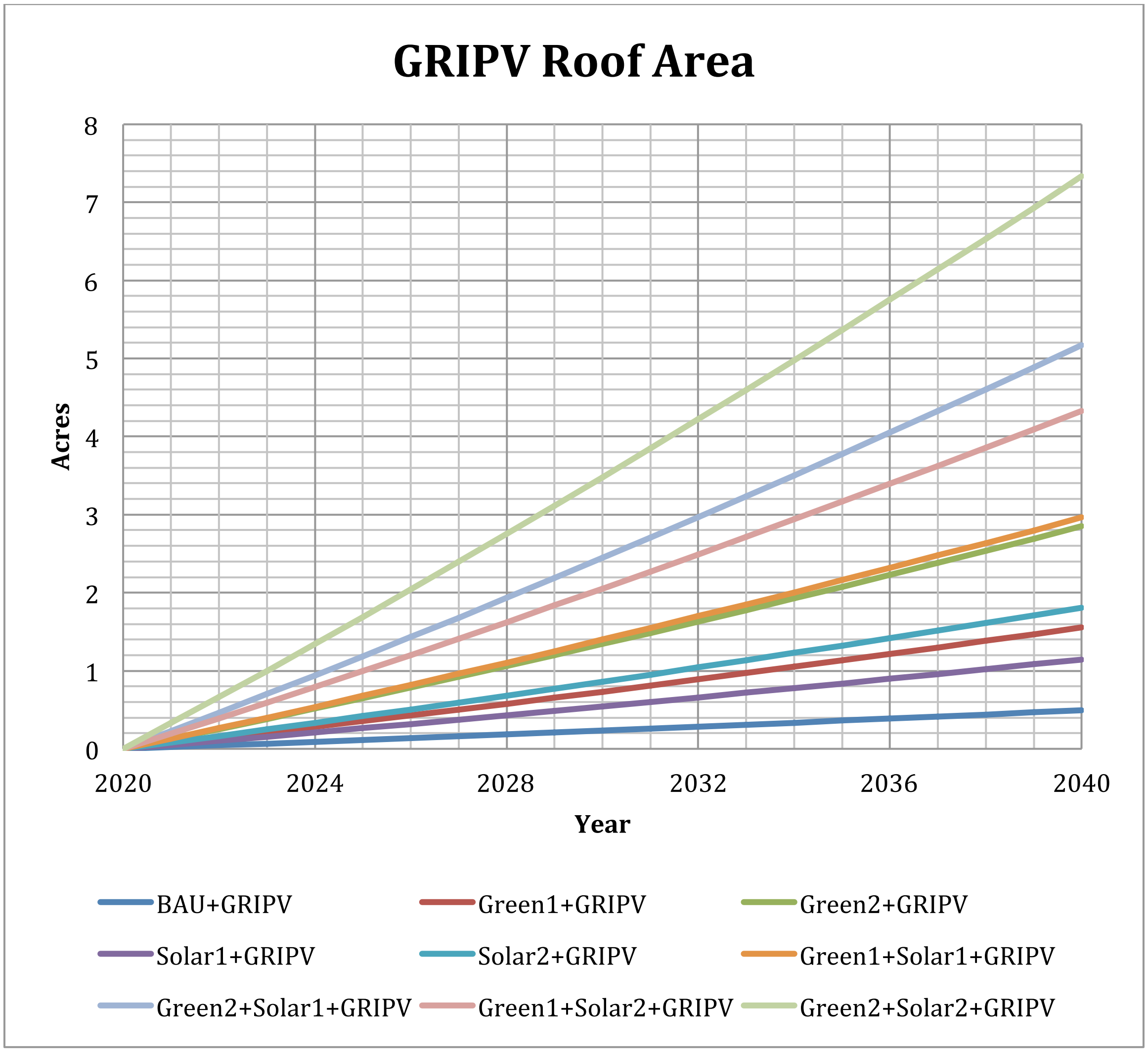


Figure 29: GRIPV Roof Area Policy Results

6.1.5 Total Annual Runoff Depth

The policy results with respect to runoff depth will not be presented graphically in this section because the resulting graphs displayed no visible change in the runoff depth in any scenario; instead, the graphical results will be included in Figures I3 and I4. The policy scenarios with the best numerical results for total runoff are the "Green2" and the

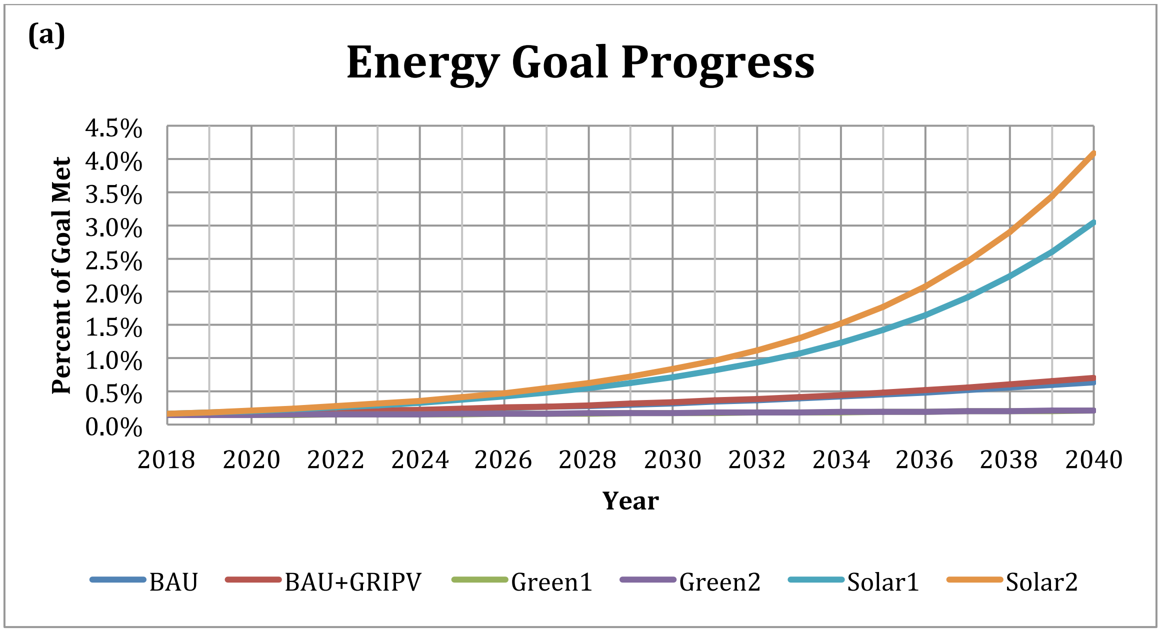
"Green2+Solar2+GRIPV" scenarios without and with the inclusion of the GRIPV market respectively. This makes sense because green roofs and GRIPV roofing have the two greatest rainfall retention rates out of all possible roofing options, while GRIPV roofing in particular has the greater potential of the two roofing options for future market growth with combined policy support for both green roofing and solar roofing individually (but even these scenarios yielded 2040 runoff reductions of no more than 0.01% compared to the 2040 runoff depth of the BAU scenario. That said, these small runoff reductions are still consistent with those in Sections 6.1.2 and 6.1.4 in that the green roof and GRIPV roof markets in Orlando are still highly underdeveloped, especially with respect to GRIPV roof systems, resulting in the market shares of each of these roofing options being less than that of solar roofing and virtually nonexistent compared to that of conventional roofing. As a result, possible runoff reductions from these two roofing markets are severely limited, and it can therefore be concluded that more intensive policy support and/or the use of external policy solutions (Section 6.1.1) may be needed to achieve greater runoff depth reductions.

6.1.6 Air Temperature Anomaly

The policy results with respect to the actual air temperature anomaly from the urban heat island effect will not be presented graphically in this section because the resulting graphs displayed no visible change in the air temperature anomaly in any scenario; instead, the graphical results will be included in Figures I5 and I6. The policy scenario with the best numerical results for air temperature anomaly is the "Solar2+GRIPV" scenarios, owing primarily to the fact that, in addition to the cooling effects of shade under the solar PV/BIPV arrays installed on the roof, solar PV/BIPV roofing can also convert solar energy into usable electricity instead of allowing it to accumulate in the solar PV/BIPV surface as waste heat, while GRIPV roofing has an even stronger cooling effect in that it combines the shading and energy redirection potentials of solar roofing with the cooling effects of evapotranspiration in green roofs. However, even in this scenario, the 2040 air temperature anomaly is only about 0.1% less than that of the BAU scenario, which is significantly larger than the improvement in runoff depth reductions mentioned in Section 6.1.5, but is still very low. That said, these findings are nevertheless consistent with those in Sections 6.1.3 and 6.1.4 in that the solar roof market in Orlando, despite being one of the most well developed solar PV/BIPV markets in the U.S., still has a long way to go before solar roofing can achieve more significant levels of market penetration, while the stronger cooling effects of GRIPV roofing have an even more strongly limited impact on the UHI effect due to its virtually nonexistent shares in the current roofing market. It can therefore be concluded that more intensive policy efforts may be needed to help the solar PV/BIPV roof and GRIPV roof markets in Orlando to grow to a more effective degree in order to achieve greater reductions in the UHI effect, while also incorporating the urban efficiency policies mentioned in Section 6.1.1 whenever possible so as to offset the increase in the UHI effect by reducing future urbanization trends.

6.1.7 Energy Goal Progress

The policy results with respect to the contribution of Orlando's alternative roofing market to Orlando's energy demand savings goals are presented graphically in Figure 30. Based on these graphs, it is immediately apparent that the solar PV/BIPV roofing market yields the greatest energy savings, partly because solar roofing currently has the most dominant market shares out of all three alternative roofing options, and partly because solar PV roofing is able to produce its own energy to offset energy requirements for buildings in addition to using shade to reduce cooling load requirements, as opposed to green roofing, which only has indirect cooling load benefits and cannot produce its own electricity. It is also interesting to note, however, that the graphs in Figure 30 demonstrate very little change in energy goal progress when GRIPV roofing is introduced into the alternative roofing market, owing in no small part to the fact that it is the newest of the three alternative roofing options and has marginal market shares compared to conventional roofing. The maximum possible energy savings goal contribution in this regard yielded only a 4.13% contribution to the established goal, meaning that it will also be necessary to consider non-roofing solar PV applications and other renewable energy and energy-saving initiatives not related to alternative roofing in addition to the alternative roofing policies analyzed in this study, as these results show that the alternative roofing market alone will not be enough to meet the established 2040 energy savings goal. As for the alternative roofing market, it can be concluded that the solar and GRIPV roofing industries can provide the greatest contributions to energy savings, but that more intensive policy efforts are once again required to improve the market penetration rates of both industries in order to yield any truly significant energy savings with respect to the 2040 energy demand goals specified for the city of Orlando.



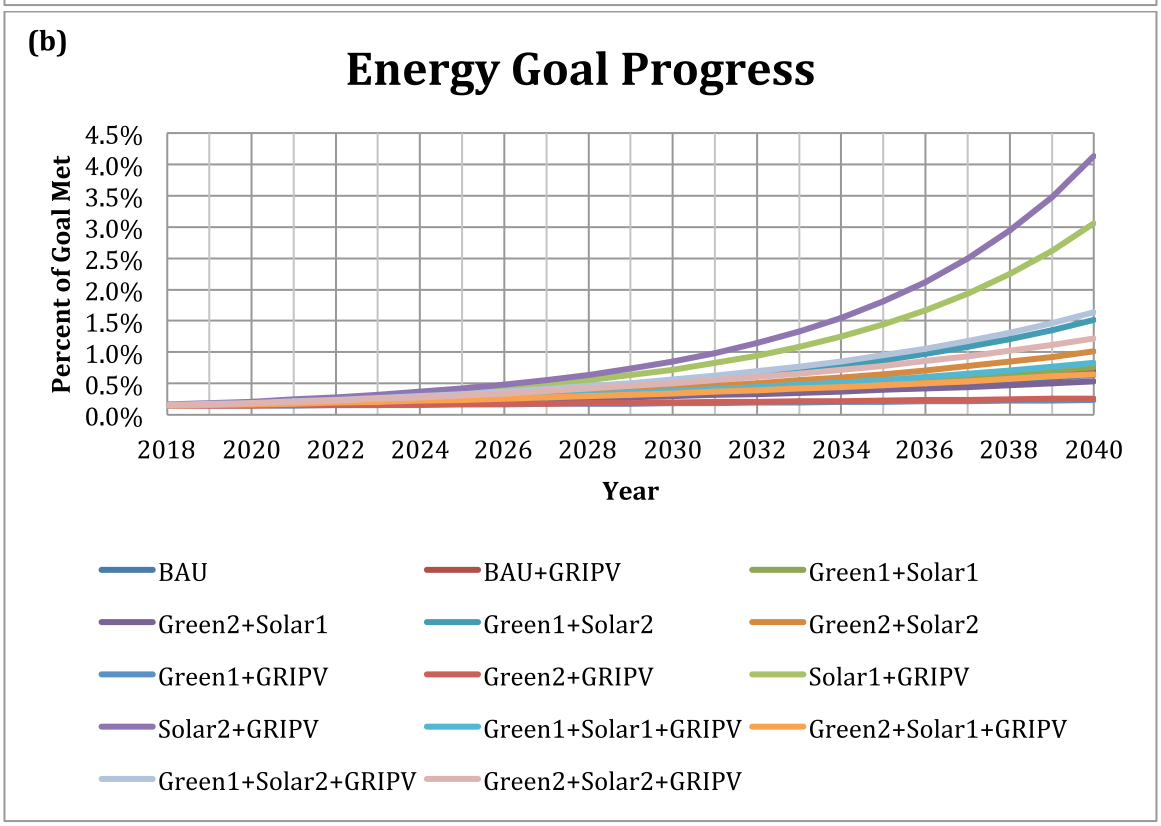


Figure 30: Energy Goal Progress Policy Results

(a) Individual Policies (b) Multiple Policies

6.1.8 GHG Goal Progress

The policy results with respect to the contribution of Orlando's alternative roofing market to Orlando's GHG emission reduction goals are presented graphically in Figure 31. The findings from these graphs are very similar to those from Figures 30 in that investments in the solar PV/BIPV roofing market yield the greatest GHG emission savings, primarily because the significant reductions in grid-based electricity demand with solar PV/BIPV and GRIPV roof systems leads to significant reductions in GHG emissions, while the benefit of carbon sequestration in green roofs is smaller in comparison. Nevertheless, it must be noted that the alternative roofing industry's overall contribution to the 2040 GHG emission goals for the city of Orlando are still very small (up to 0.35%) despite the significant changes in goal contributions between scenarios. This should not be taken to mean that the alternative roofing market contributes less to GHG emission savings goals than to energy savings goals, however, as the energy savings goal has a much smaller basis for comparison (energy savings *per capita* vs. *total* GHG emission savings) while the GHG emission savings goal is evaluated based on the total 2007 emission rate in 2007 (including emissions not related to energy consumption). Overall, like with the results in Section 6.1.7, it can be concluded that the solar and GRIPV roofing industries can provide the greatest contributions to energy savings, but that more intensive policy efforts are once again required to improve the market penetration rates of both industries in order to yield any truly significant energy savings with respect to the 2040 energy demand goals specified for the city of Orlando.

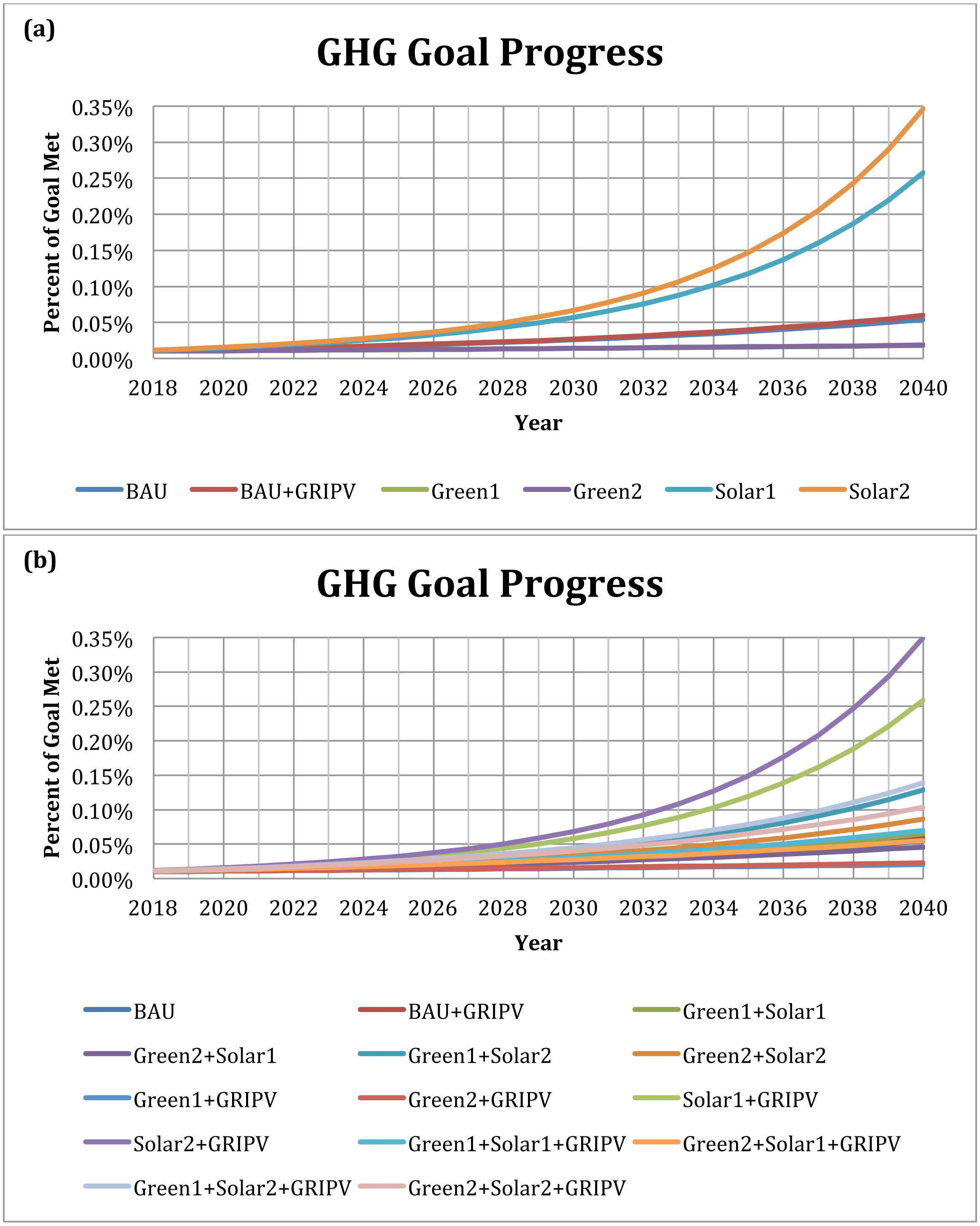


Figure 31: GHG Goal Progress Policy Results

(a) Individual Policies (b) Multiple Policies

6.2 Uncertainty Analysis Results

The uncertainty analysis performed in this study was simulated under BAU and BAU+GRIPV simulation conditions (i.e. no policy implementations) in order to illustrate the inherent degrees of uncertainty in the output variables previously discussed in Section 6.1 without the inclusion of external policy implementation. For this purpose, separate graphs and discussions will be provided for each output variable in Sections 6.2.1 through 6.2.8, and histograms corresponding to each set of uncertainty results will be provided in Appendix J.

6.2.1 Conventional Roof Area

The uncertainty results with respect to conventional roof area are presented graphically in Figures 32 (BAU) and 33 (GRIPV only). Unlike the policy analysis results for conventional roof area (Section 6.1.1), which showed no graphically significant changes between policies, the corresponding uncertainty analysis results demonstrate a clear potential for the alternative (esp. solar) roofing market to gain a more stable foothold in Orlando's roofing industry under certain market conditions, with a visible possibility for conventional roof area to reduce its current increasing trends starting by at least 2026, while the corresponding histograms (Figure J3) show that the minimum conventional roof area possible in this regard could potentially reach between 29,160 acres and 29,480 by 2040 (a decrease of 3,461-3,781 acres compared to BAU conditions). Based on the uncertainty analysis results for the three alternative roofing options (Sections 6.2.2 through 6.2.4), this potential boom in the alternative roofing market is most likely to come from the solar roofing industry, which is no surprise due to its relative maturity as well as its receptiveness to positive policy influences as previously demonstrated in Section 6.1.3.

These optimistic uncertainty results with respect to solar roofing once again demonstrate that it will most likely continue to be a primary driving force for reducing conventional roofing market shares and encouraging future growth in the alternative roofing market industry as a whole, while the relatively newer green and GRIPV roof industries will require more extensive policy investment and overall development before they can reach the same level of market maturity.

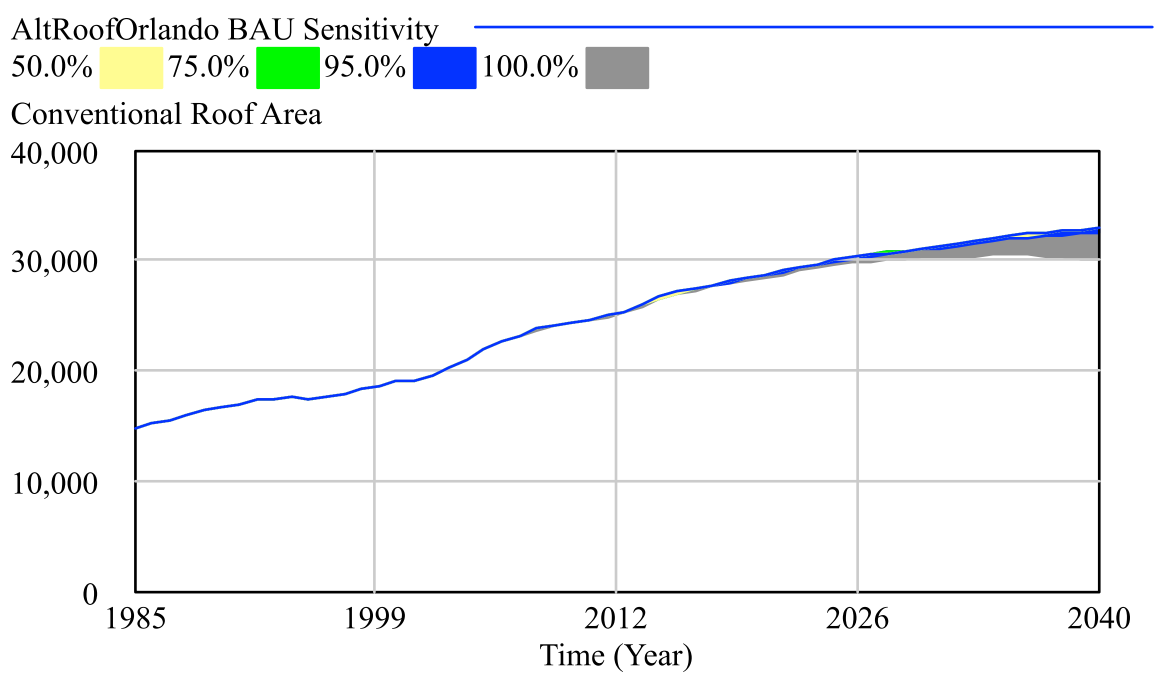


Figure 32: Conventional Roof Area BAU Uncertainty Graph

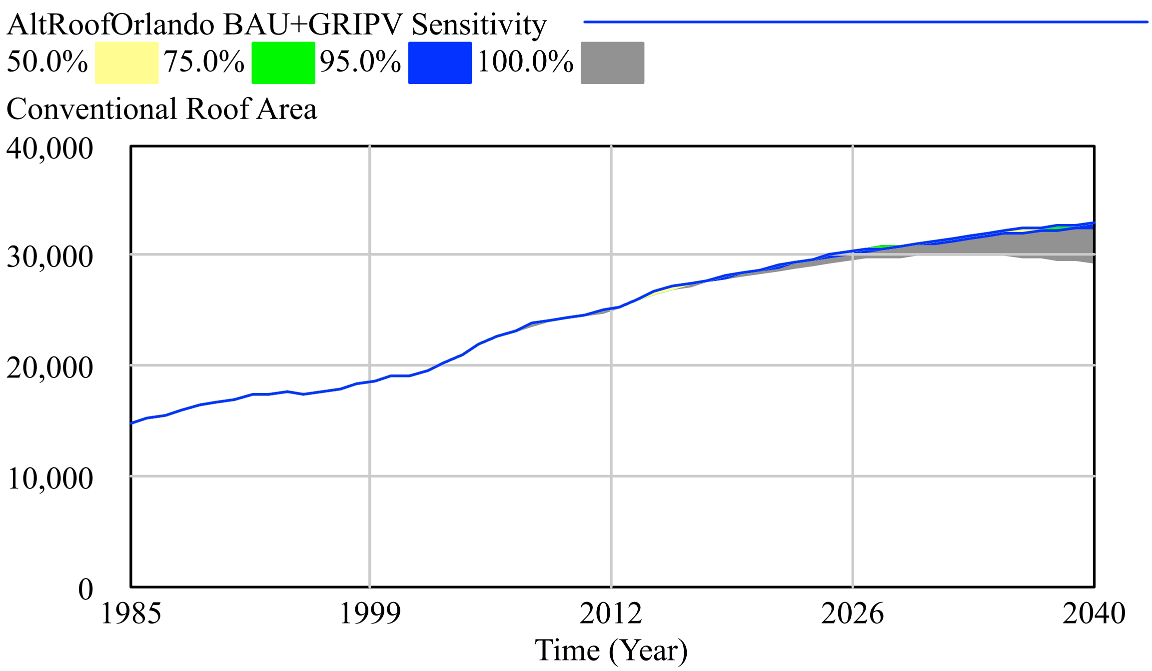


Figure 33: Conventional Roof Area GRIPV-Only Uncertainty Graph

6.2.2 Green Roof Area

The uncertainty results with respect to green roof area are presented graphically in Figures 34 (BAU) and 35 (GRIPV only). These graphs highlight the same conclusions drawn in Section 6.1.2 in that the green roof market is not particularly sensitive to external variable uncertainties, with possible 2040 total green roof acreage values ranging only from approximately 1.1 acre to approximately 1.3 acres overall. In other words, without sufficient policy intervention, green roof market penetration in Orlando is unlikely to deviate from its historical growth trends to any significant degree, although the introduction of GRIPV systems made green roof market potential more likely overall to increase as shown in the corresponding histograms (Figure J4).

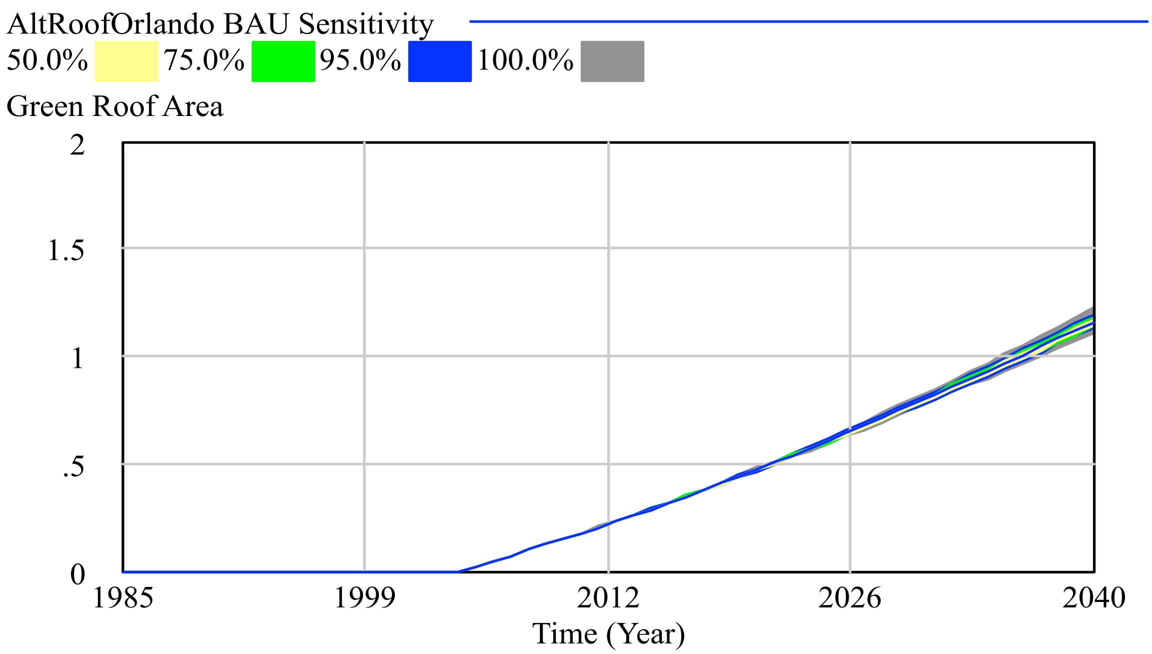


Figure 34: Green Roof Area BAU Uncertainty Graph

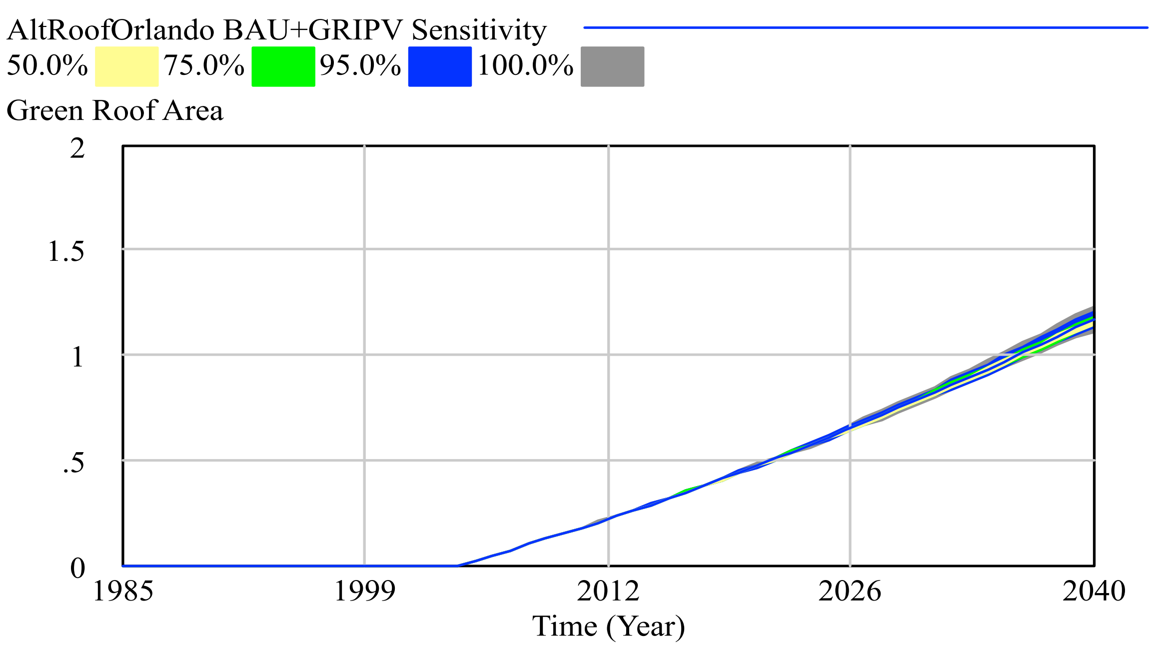


Figure 35: Green Roof Area GRIPV-Only Uncertainty Graph

6.2.3 Solar Roof Area

The uncertainty results with respect to solar roof area are presented graphically in Figures 36 (BAU) and 37 (GRIPV only). In contrast to the green roof uncertainty results in Section 6.2.2, solar roof market penetration is shown to be highly sensitive to variations in external factors, with final 2040 solar roof areas potentially reaching as high as 3,000 acres without the inclusion of the GRIPV roof market and up to 3,840 acres with the inclusion of the GRIPV market, although BAU solar roof area is more likely (within 95% confidence) to reach up to approximately 500 acres, with a more conservative majority of the simulation results still potentially reaching as high as 320 acres based on the corresponding histograms (Figure J5). These results clearly demonstrate that it is highly possible for solar PV/BIPV roofing to emerge as a dominant option in the alternative roofing market as a whole by the year 2040 with sufficient improvement in PV/BIPV technology and market conditions, which in turn would result in major improvements in the environmental impacts in which solar PV/BIPV market penetration was found to be a viable solution (the UHI effect, energy savings, and GHG emission reductions). Such advancements should therefore be pursued and encouraged whenever they may be feasible, especially since solar roofing's primary alternative roofing competitor (green roofs) has previously been shown not to be too sensitive to these same advancements.

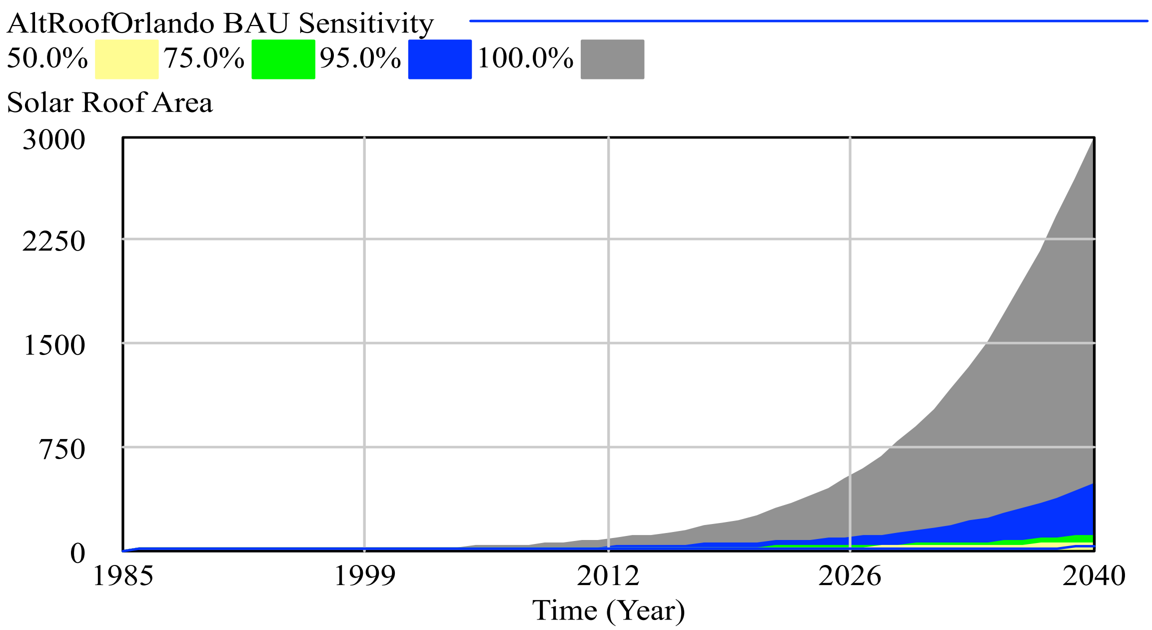


Figure 36: Solar Roof Area BAU Uncertainty Graph

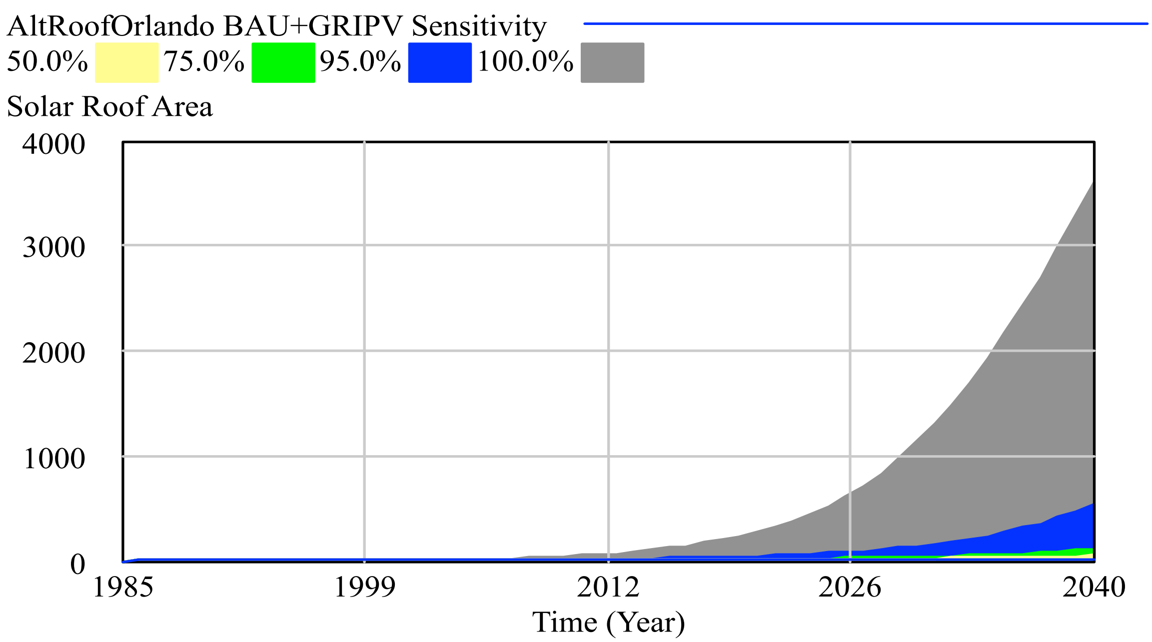


Figure 37: Solar Roof Area GRIPV-Only Uncertainty Graph

6.2.4 GRIPV Roof Area

The uncertainty results with respect to GRIPV roof area are presented graphically in Figure 38 (GRIPV only). Much like with the green roof uncertainty results in Section 6.2.2, GRIPV roof market penetration is shown not to be particularly sensitive to variations in external factors, with the corresponding histogram (Figure J6) showing that final 2040 GRIPV roof areas are likely to reach no higher than 0.51 acres without any policy implementations and never reaching lower than 0.46 acres. In other words, again like with green roofing, the GRIPV market will require significant policy intervention to support and encourage its growth at this early stage, regardless of other possible advancements in technology. Furthermore, it is worth noting that the uncertainty results for GRIPV roofing tend to follow a trend most similar to the corresponding results for green roofing, meaning that market conditions in the green roofing industry can have a particularly strong influence on the GRIPV market.

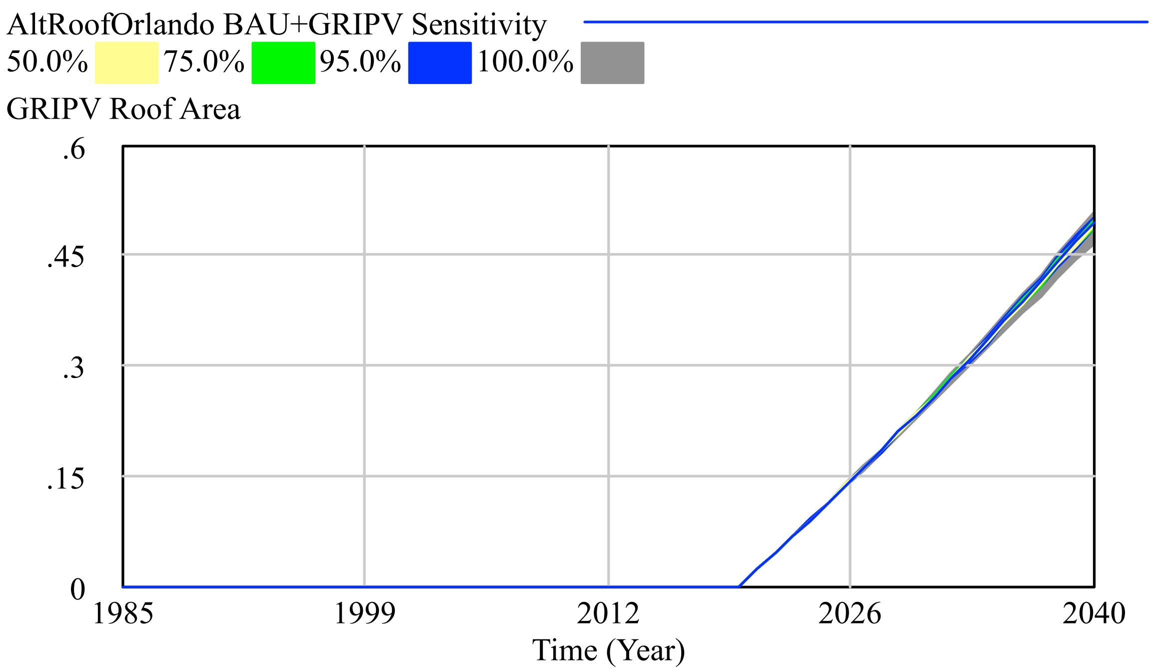


Figure 38: GRIPV Roof Area Uncertainty Graph

6.2.5 Total Annual Runoff Depth

The uncertainty results with respect to annual runoff depth will not be presented graphically in this section because no significant variability could be observed in the corresponding uncertainty analysis; instead, these graphs will be presented in Figures J1 and J2 in Appendix J. Based on the corresponding histograms (Figure J7), the entire range of possible 2040 runoff depths falls between 18.688 inches and 18.714 inches, although these upper and lower limits are too close together to clearly illustrate the precise degree of variability within this range. Nevertheless, this complete absence of variability in runoff depth in spite of the possible variations in external parameters makes it clear it will not be enough to rely solely on improvements and advancements in other external factors, and could also be due to the fact that impervious surfaces comprise over 99% of construction and alternative roofing materials in today's market, whereas the market penetration rates of the only two roofing markets that could potentially reduce urban runoff (green roofing and GRIPV roofing) are either marginal or nonexistent under a BAU or BAU+GRIPV scenario.

Overall, these findings indicate that urban runoff in Orlando will be a difficult issue to resolve on a large-scale, long-term basis, but can be addressed to at least some extent through the urban efficiency policy efforts previously discussed in Section 6.1.1, in addition to encouraging the advancement and implementation of pervious surfaces for construction projects (green/GRIPV roofing, pervious pavement, etc.) as viable alternatives to conventional construction materials will also be essential for reducing runoff in the long run and thus making the construction industry more sustainable, especially in situations where the above-mentioned development efficiency policies may not be feasible enough to be effective. However, as previously noted and discussed, there are still many practical and economic obstacles to overcome in this regard before such alternatives can reduce runoff on a macro-level scale to any significant degree.

6.2.6 Air Temperature Anomaly

The uncertainty results with respect to air temperature anomaly are presented graphically in Figures 39 (BAU) and 40 (GRIPV only). Despite these uncertainty results possibly reaching as high as $+2.2^{0}$F in 2040 and the lack of significant improvements in the policy analysis results in Section 6.1.6, the uncertainty results in Figures 39 and 40 indicate that the UHI effect can potentially be reduced to a temperature anomaly as low as $+0.52^{0}$F, with a slight leftward skew in the corresponding 2040 histogram results when the GRIPV roofing market was included

(Figure J8). Furthermore, the maximum possible 2040 temperature anomaly decreased to less than +2.0^{0}F when GRIPV roofing was included as a possible option, and it is likewise apparent that UHI impacts in Orlando will be heavily dependent on costs, technology, and other critical external factors in the urban roofing industry as a whole (esp. the albedos, PV energy efficiencies, and other cooling-related factors of the more dominant conventional and alternative roof surface types). These results therefore highlight the importance of managing these external factors as they apply to all conventional and alternative roof types, with the aid of technological improvements, cost reductions, and other such initiatives whenever possible. The solar roofing industry, being consistently the dominant option among the three alternative roof types due to its market maturity in addition to having control over many of these external factors to varying extents, is also especially likely to be a long-term contributor to reductions in the UHI effect as solar PV technology improves over time, especially if and when GRIPV roofing systems become available. Lastly, since new construction (esp. with conventional building materials) is a primary contributor to the UHI effect, the additional policy initiatives discussed in Section 6.1.1 in this regard can also be very effective for reducing the UHI effect.

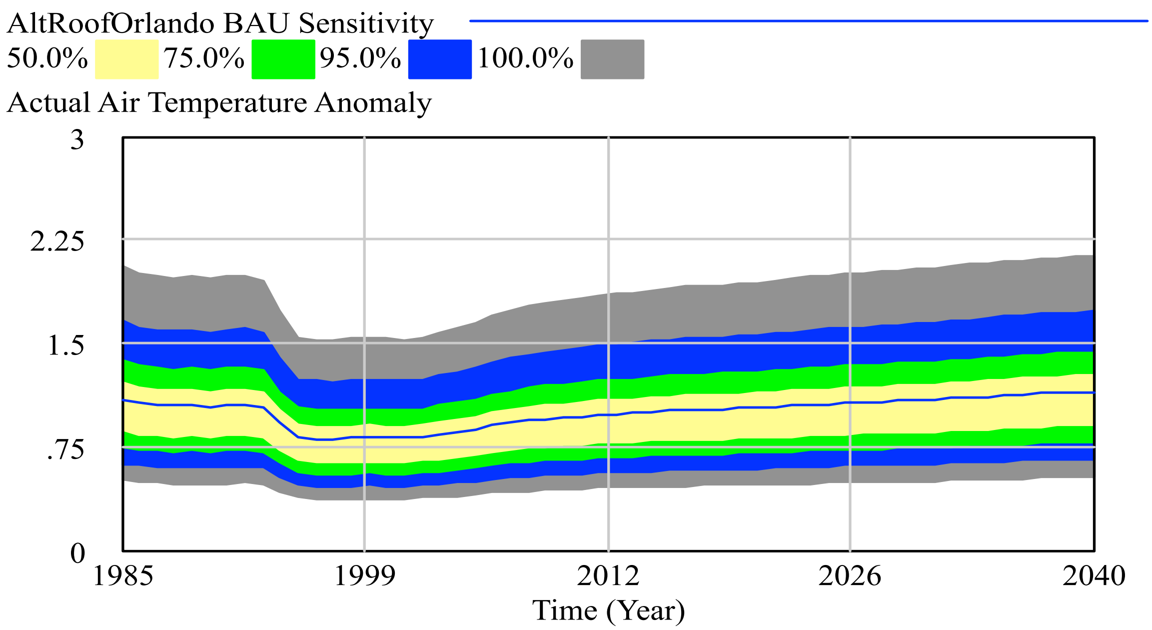


Figure 39: Air Temperature Anomaly BAU Uncertainty Graph

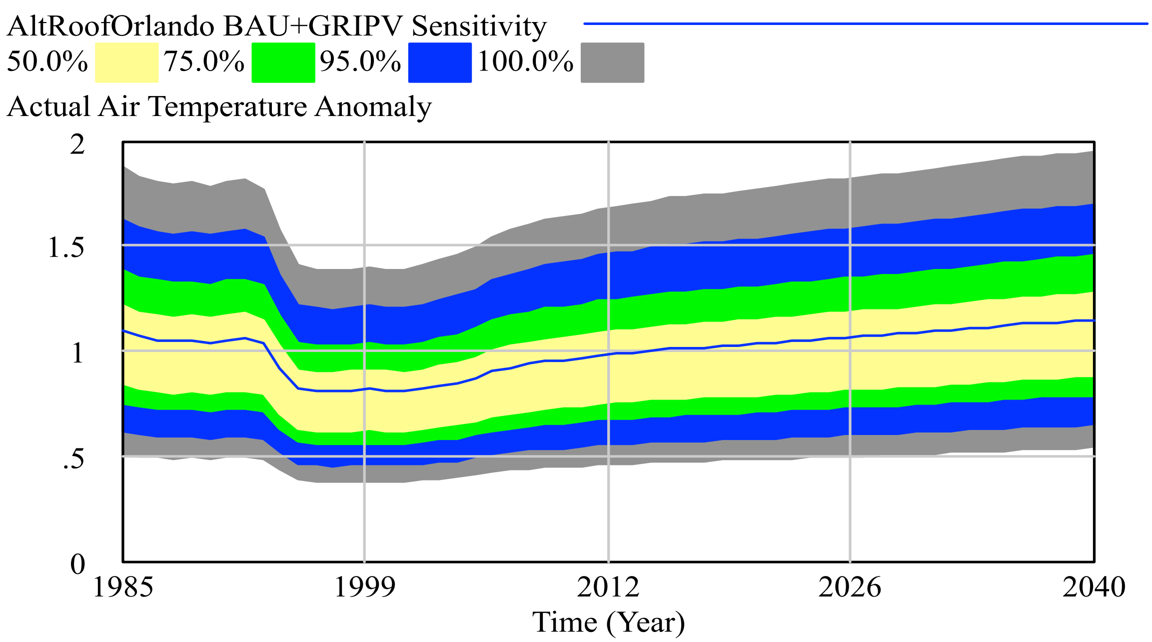


Figure 40: Air Temperature Anomaly GRIPV-Only Uncertainty Graph

6.2.7 Energy Goal Progress

The uncertainty results with respect to energy savings goal progress are presented graphically in Figures 41 (BAU) and 42 (BAU+GRIPV). Despite the policy results in Section 6.1.7 reaching less than 5% progress in all scenarios, the corresponding uncertainty results in this section are far more optimistic. The vast majority of the simulation results were limited to 11% of goal progress by 2040 as shown in the uncertainty histograms (Figure J9), but the 95% confidence range achieved progress levels of up to approximately 20% with and without the introduction of GRIPV roofing, while the corresponding total possible ranges (100% confidence) indicate the potential to nearly meet or (if GRIPV roofing is available as an option) to possibly exceed the established 2040 goal. Based on the uncertainty results for the three alternative roof types included in the model (Sections 6.2.2 through 6.2.4), this is most likely due to the fact that Orlando has one of the largest and most advanced solar PV/BIPV energy markets in the U.S., allowing it to more significantly contribute to energy demand savings with sufficient improvements in costs, technology, and other critical external factors (esp. energy efficiency), especially if and when GRIPV roofing systems can be made available. These results therefore highlight the importance of managing these external factors through technological improvements, cost reductions, and other such initiatives whenever possible.

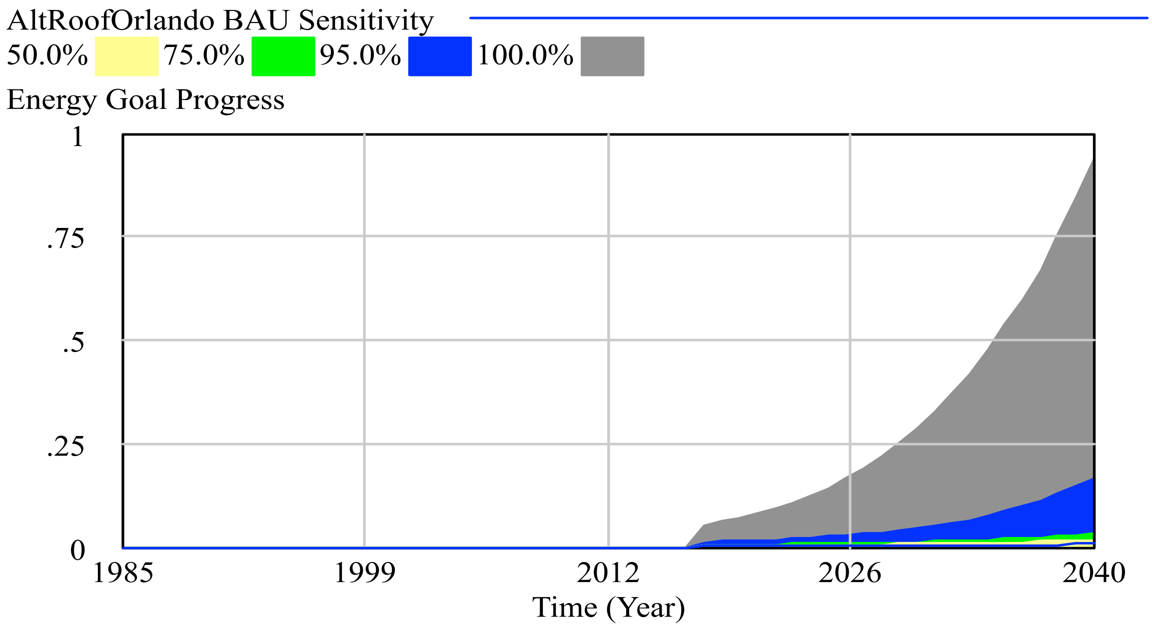


Figure 41: Energy Goal Progress BAU Uncertainty Graph

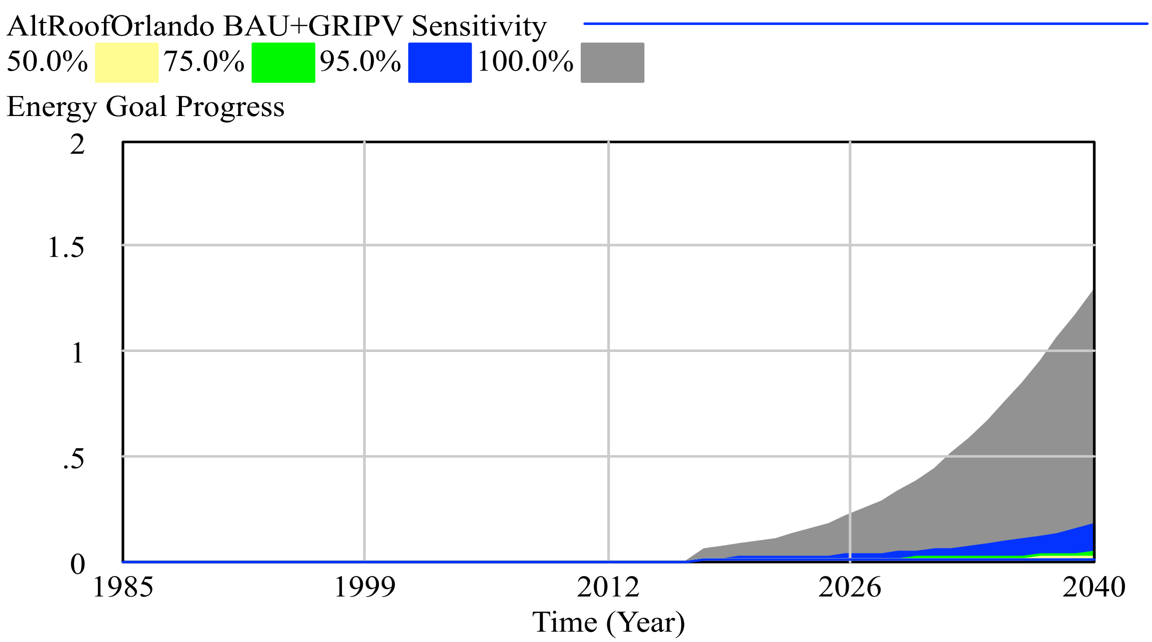


Figure 42: Energy Goal Progress GRIPV-Only Uncertainty Graph

6.2.8 GHG Goal Progress

The uncertainty results with respect to GHG emission reduction goal progress are presented graphically in Figures 43 (BAU) and 44 (GRIPV only). Although these uncertainty results still do not come close to meeting the established 2040 goal on their own, with a majority of the uncertainty results at 0.95% of goal progress as shown in the corresponding histograms (Figure J10), they do indicate the possibility of a major improvement over the policy analysis results in Section 6.1.8, this time reaching a maximum of 8% of the GHG emission goal without GRIPV roofing and 11% with GRIPV roofing. Based on the uncertainty results for the three alternative roof types included in the model (Sections 6.2.2 through 6.2.4), this is most likely due to the energy savings potential of the solar PV/BIPV roofing industry (which is a primary contributor to GHG emission savings as simulated in the model) in light of the fact that Orlando has one of the largest and most advanced Solar PV/BIPV energy markets in the U.S., allowing it to more significantly contribute to GHG emission savings with sufficient improvements in costs, technology, and other critical external factors (esp. energy efficiency). These results therefore highlight the importance of managing these external factors through technological improvements, cost reductions, and other such initiatives whenever possible. However, since not even the most optimistic possible scenario in this regard was able to meet the established 2040 goal, it is also clear that the 2040 GHG emission reduction goal cannot be met through the alternative roofing market alone, meaning that GHG emission reduction methods for sectors not covered in this model (e.g. the transportation sector) will also be necessary to achieve this goal.

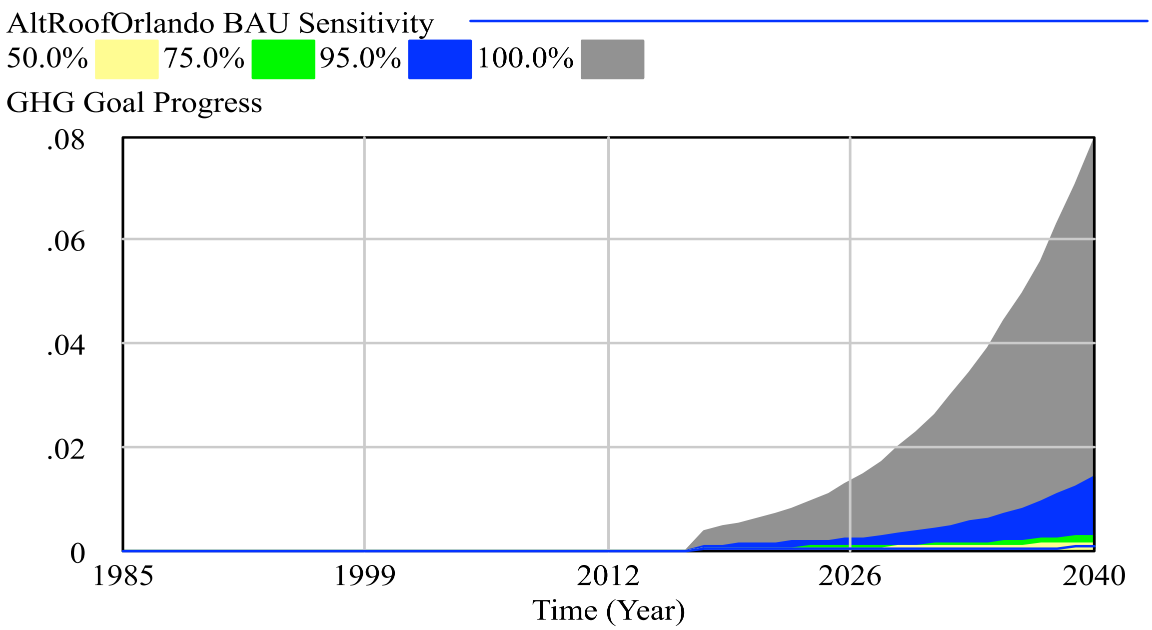


Figure 43: GHG Goal Progress BAU Uncertainty Graph

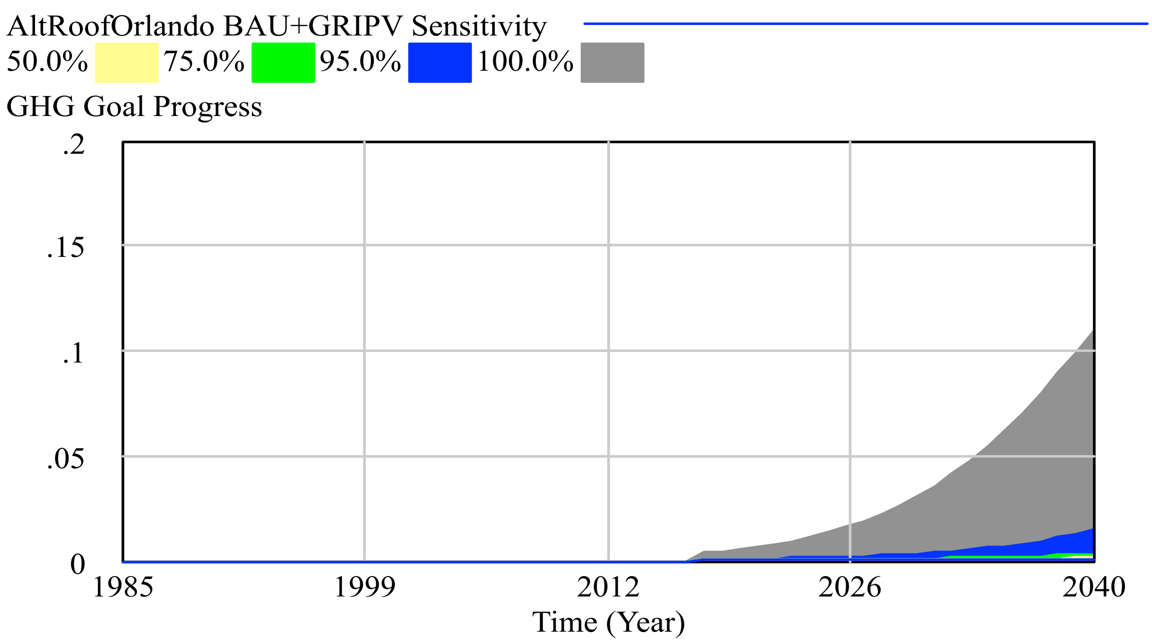


Figure 44: GHG Goal Progress GRIPV-Only Uncertainty Graph

6.3 Case Study Analysis Results

As previously noted in Section 5.3, the case study conducted as part of this research consists of:

1. A *case study policy analysis* to evaluate financial incentives per unit of alternative roofing and/or bylaws requiring alternative roofing adoption for certain types of new non-residential development each year, and
2. A *case study uncertainty analysis* to evaluate the overall degree of uncertainty involved in the application of the policies tested in the case study policy analysis, accounting for the same ranges and probability distributions as in the previous uncertainty analysis (Sections 5.2 & 6.2) as well as the full range of possible applications of the above-mentioned case study policies (Table H7), including the range of historically-applied financial incentives per unit development of alternative roofing and all possible ranges with respect to the application of alternative roofing adoption bylaws.

The results of these analyses will be discussed in further detail in Sections 6.3.1 and 6.3.2, respectively.

6.3.1 Case Study Policy Analysis Results

The results of the case study policy analysis have been broken down into Sections 6.3.1.1 through 6.3.1.7 with respect to each individual output variable. For easier reference, a full summary of all optimal policy scenarios with respect to each output is provided in Table 28 below. These optimal results will be discussed in further detail in each of their respective subsections. From this table, it is immediately apparent that the use of alternative roofing bylaws, which target new roofing construction rather than the "retrofitting" of pre-existing conventional roofs, can result in dramatic improvements in the market penetration of any given type of alternative roofing and in turn yield more significant improvements in each of the considered environmental impacts than what was observed in the original policy analysis results from Section 6.1, where the main policy focus was on the retrofitting of pre-existing conventional roofs (e.g. a 0.25% maximum decrease in "Air Temperature Anomaly" in Table 28 versus a 0.1% maximum decrease in Table 27). This finding highlights one of the general disadvantages of the alternative roofing markets (esp. green roofing) previously discussed in Chapter 1 in that they are typically best suited for newly constructed roofs that can be designed to accommodate them properly and utilize them to their full potential, as opposed to retrofits of pre-existing roofs that may or may not be able to support such roofing systems. In other words, it is especially recommended for future alternative roofing policy efforts to emphasize the adoption of alternative roofing for new urban development.

Table 28: Summary of Optimal Case Study Policy Scenarios for Each Output

Output Variable	*Optimal Case Study Policy Scenario(s)*	*Best Year 2040 Value*	*Change v.s. 2040 BAU Value*	*Change v.s. 2040 GRIPV Only Value*
Conventional Roof Area	SolarBylaw	31,577 acres	-4.142%	-4.135%
Green Roof Area	GreenBylaw	799 acres	+68,705%	+68,413%
Solar Roof Area	SolarBylaw	1,384 acres	+6,977%	+6,424%
GRIPV Roof Area[a]	GRIPVBylaw	659 acres	N/A	+133,119%
Runoff Depth	GreenBylaw GreenEco+GreenBylaw	18.55 inches	-0.865%	-0.865%
Air Temperature Anomaly	GreenBylaw GreenEco+GreenBylaw	+1.125^{0}F	-2.02%	-2.02%
Energy Goal Progress	SolarBylaw	45.16% of goal met	+6,966%	+6,334%
GHG Goal Progress	SolarBylaw	3.82% of goal met	+6,948%	+6,319%

[a]The BAU scenario does not include GRIPV market penetration.

6.3.1.1 Conventional Roof Area

The bylaw case study policy results with respect to conventional roofing are presented in Figures 45 through 48. The non-bylaw results will not be shown graphically in this section because the corresponding graphs do not show any visibly significant change in the graphical trends in the results; these graphs will instead be presented in Figures K1 and K2. The results demonstrate clearly visible reductions in conventional roofing (thus indicating clear increases in the overall market shares of alternative roofing) under most policy scenarios, but the maximum possible decrease is still very small (up to 4.142% compared to the BAU scenario), owing primarily to the fact that even the highest observed alternative roofing market penetration levels are still far smaller than the corresponding conventional roof acreage. Nevertheless, this finding highlights a definite potential for the alternative roofing industry to achieve more prominent (though still relatively small) market shares in Orlando's roofing industry with even a relatively conservative application of alternative roofing bylaws. These results also once again highlight the greater maturity of the solar roofing market, as the "SolarBylaw" scenario resulted in the greatest reductions (though comparable results were still observed for all other bylaw scenarios), while the bylaw results clearly demonstrate the potential effectiveness of alternative roofing adoption strategies for newly constructed development in addition to the retrofitting of pre-existing construction. Finally, it is worth noting that the use of financial support in conjunction with roofing bylaws had little effect on the reduced conventional roofing market shares from the application of such bylaws, although slight reductions in conventional roof area (esp. due to increased solar roof area, as discussed in Section 6.3.1.3) were still observed in this regard with respect to the more "permissive" policy scenarios (e.g. "BothBylaw" or "AllThreeBylaw") in which all available alternative roofing markets were targeted. In other words, although the use of such incentives to provide bylaw support is unlikely to have any significant long-term impact on the conventional or alternative roofing markets in terms of overall market penetration, these results also mean that financial incentives can still be offered in reasonable amounts whenever possible (esp. in a balanced policy scenario) to help building owners with investment costs, especially if "indirect" financial incentives can be offered by increasing the likelihood of greater operational savings (e.g. wastewater and/or electricity discounts).

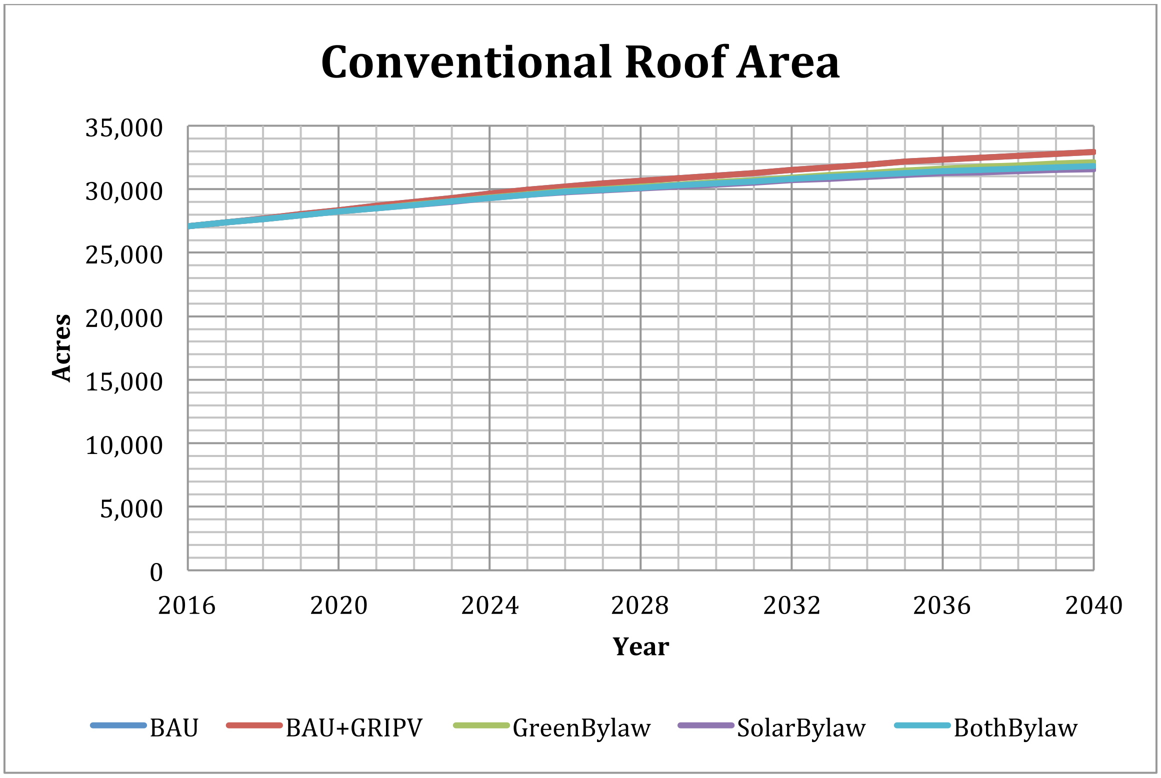


Figure 45: Conventional Roof Area Case Study Policy Results – Bylaws Only

(No GRIPV Market)

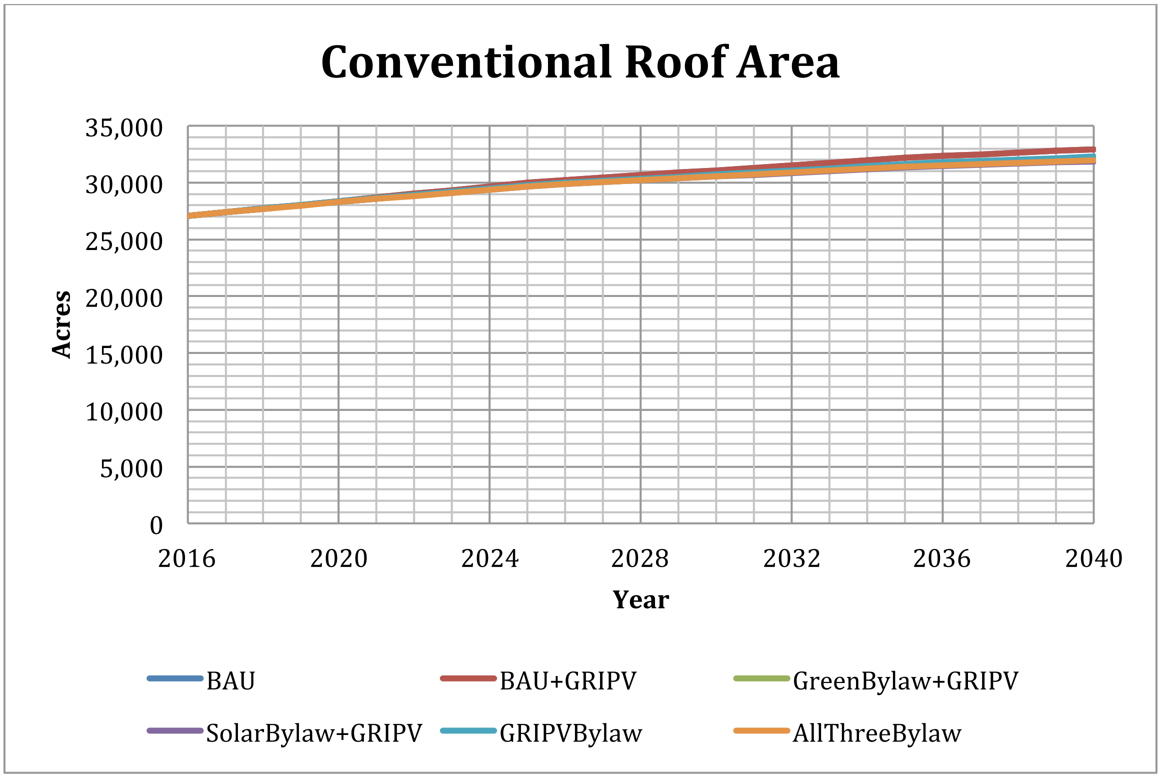


Figure 46: Conventional Roof Area Case Study Policy Results – Bylaws Only

(GRIPV Included)

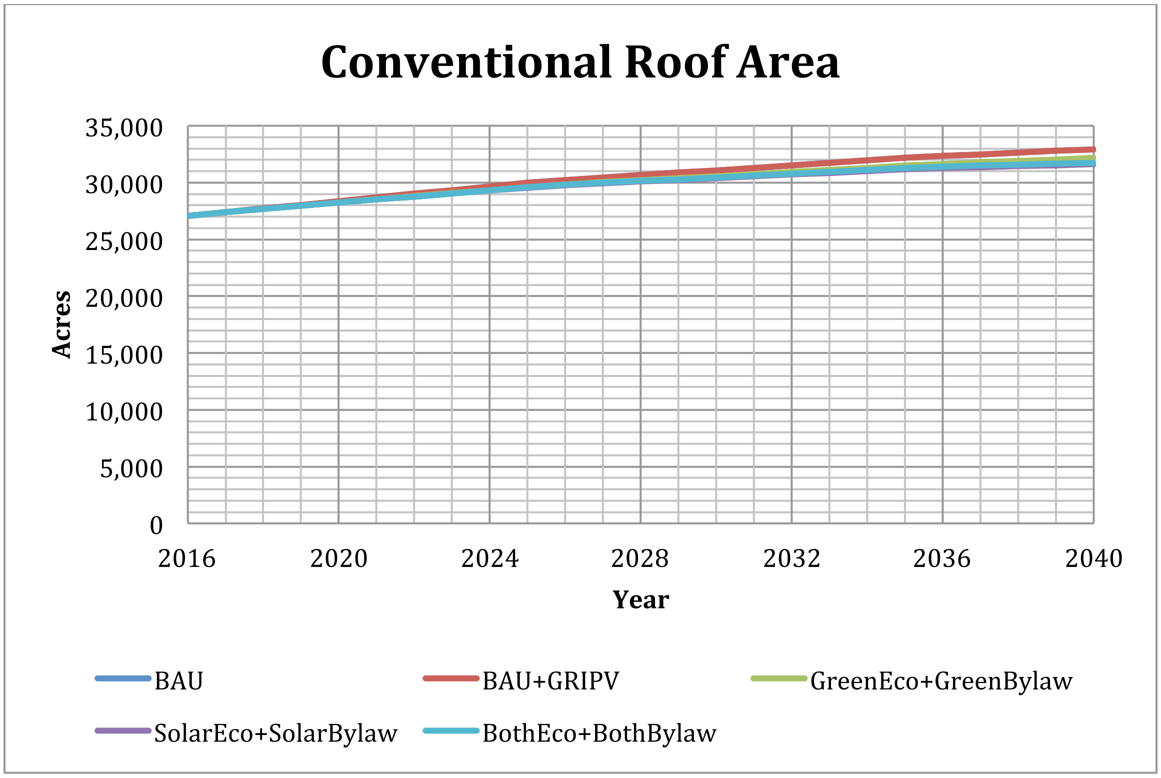


Figure 47: Conventional Roof Area Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

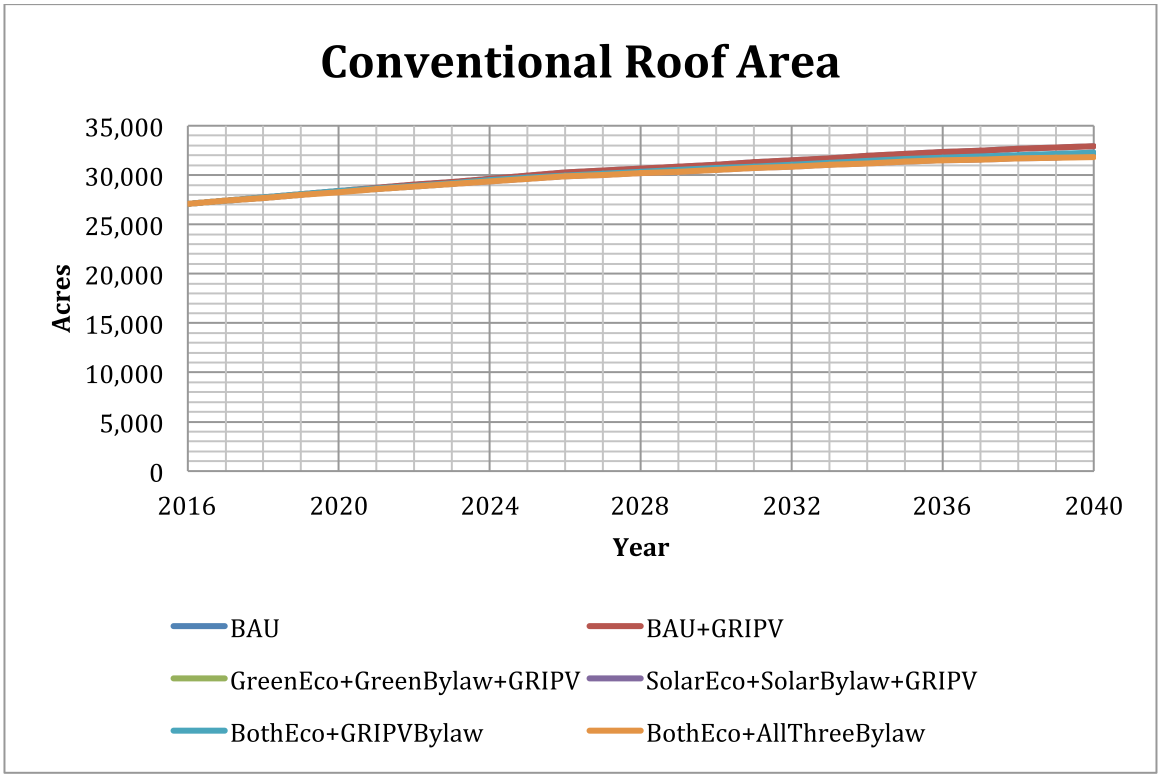


Figure 48: Conventional Roof Area Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.2 Green Roof Area

The bylaw case study policy results with respect to green roof area are presented graphically in Figures 49 through 52. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the BAU scenario; these graphs will instead be presented in Figures K3 and K4. As shown in these graphs, green roof market penetration is understandably at its highest with roofing bylaws that more specifically focus on the adoption of green roofing, with green roof area reaching as high as 799 acres in 2040 under the "GreenBylaw" scenario as opposed to 1.16 acres under the BAU scenario. However, it must be noted that all bylaw scenarios in which green roofing was an available option also yielded significantly higher market penetration levels than that of the BAU scenario. For instance, the “AllThreeBylaw” scenario had all three alternative roof types as available options and was therefore the least stringent bylaw scenario for the adoption of any particular alternative roof option, but the green roof market penetration under this scenario was still significantly higher than that of the BAU scenario (267 acres versus 1.16 acres). As previously noted, this finding highlights the importance of focusing on encouraging green roof adoption for new urban development, which generally has greater potential for the successful adoption of green roofs and other types of alternative roofing; this is especially true from a practical standpoint, as green roofs work best on buildings specifically designed and constructed to accommodate them. Due to its relative lack of market maturity, however, “Green Roof Area” slowly reduced its increased trends over time in later years.

On another note, it was observed that the offering of financial incentives for green roofing resulted in a relatively minor decrease in green roof market penetration (e.g. 799 acres in 2040 under the “GreenBylaw” scenario versus 775 acres in 2040 under the “GreenEco+GreenBylaw” scenario), which may indicate a reduction in the feasibility of using financial incentives to support the effectively forced adoption of the alternative roofing type(s) specified in the bylaw requirements, especially as said bylaw requirements focus more specifically on a particular alternative roofing option and thus require financial support for higher levels of penetration. That said, it must be noted that this decrease is virtually negligible compared to the overall benefits relative to the BAU scenario. For instance, despite a decrease in 2040 green roof area of 24 acres between the “GreenBylaw” and “GreenEco+GreenBylaw” scenarios, the 2040 green roof area under the "GreenEco+GreenBylaw" scenario is still far greater than that of the BAU scenario, meaning that the overall market penetration benefits from green roofing bylaws still far outweigh any apparent drawback from the cost of offering financial support. Nevertheless, it is still highly recommended for such financial incentives to focus on operational savings (e.g. wastewater cost discounts for green roof owners) where possible, thereby requiring less direct financial support from the government and/or from other private entities and in turn reducing or even eliminating any adverse feasibility impacts.

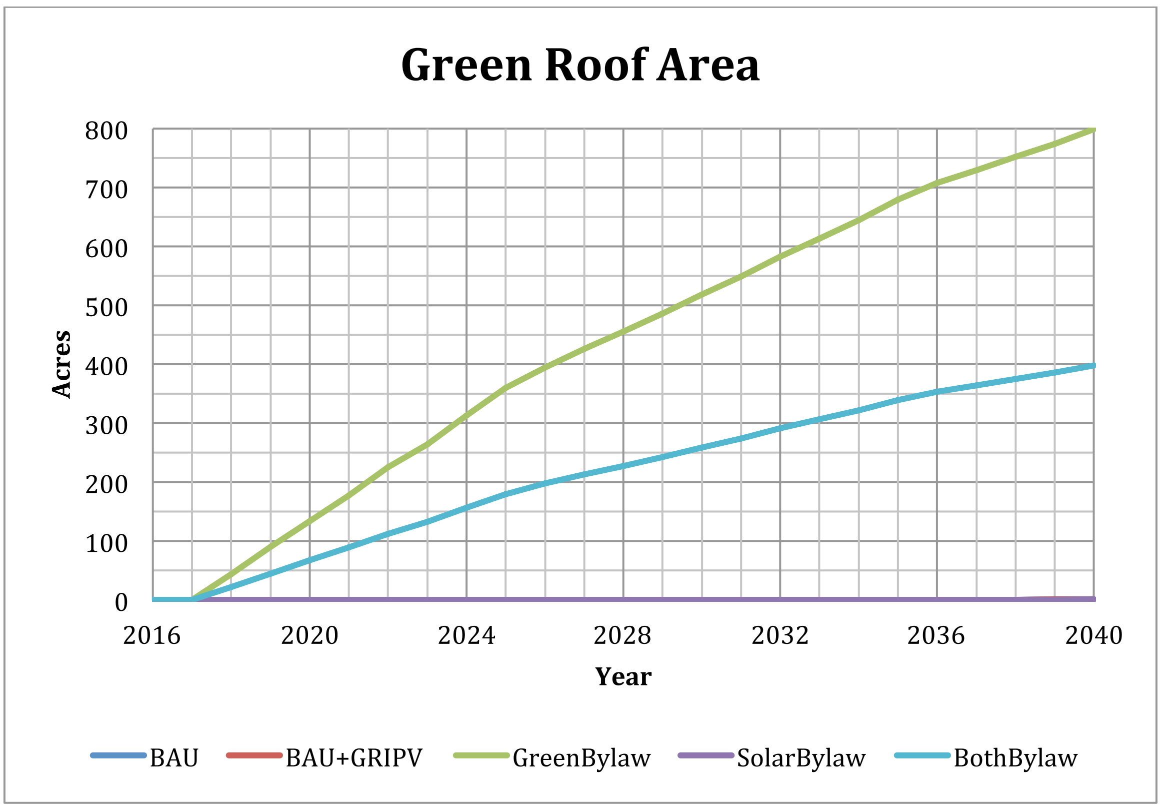


Figure 49: Green Roof Area Case Study Policy Results – Bylaws Only

(No GRIPV Market)

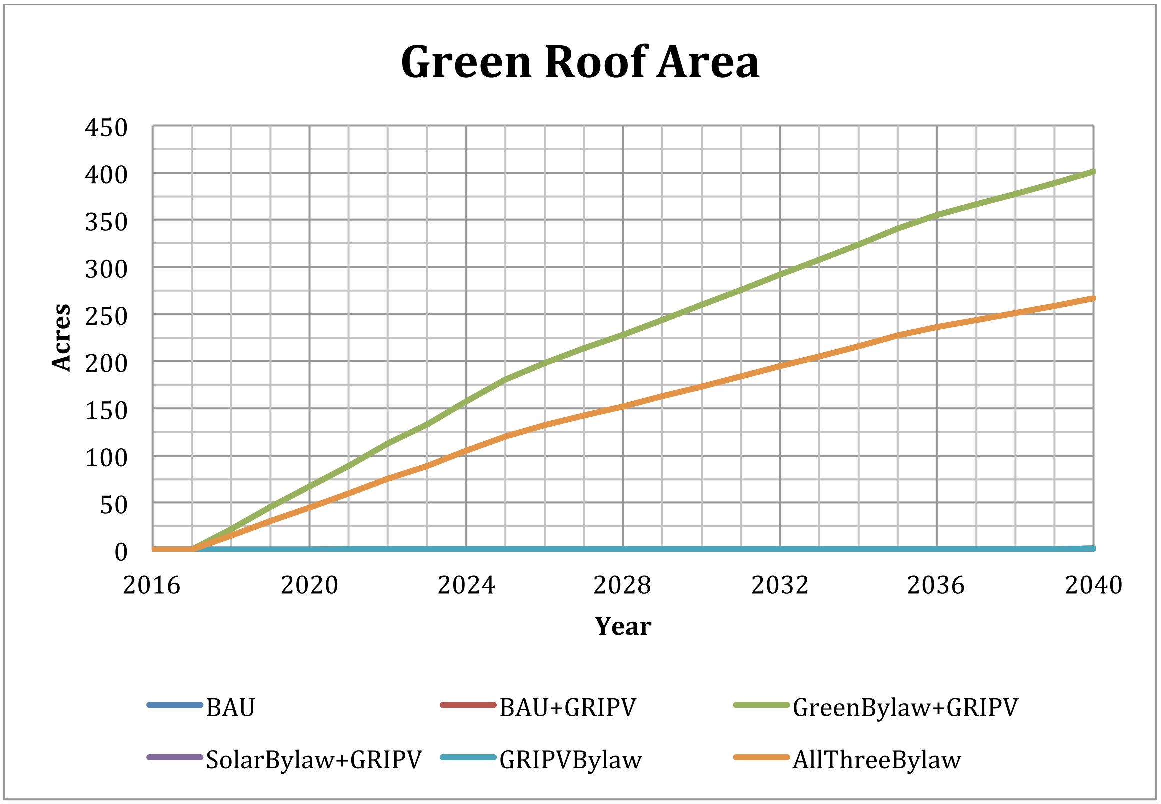


Figure 50: Green Roof Area Case Study Policy Results – Bylaws Only

(GRIPV Included)

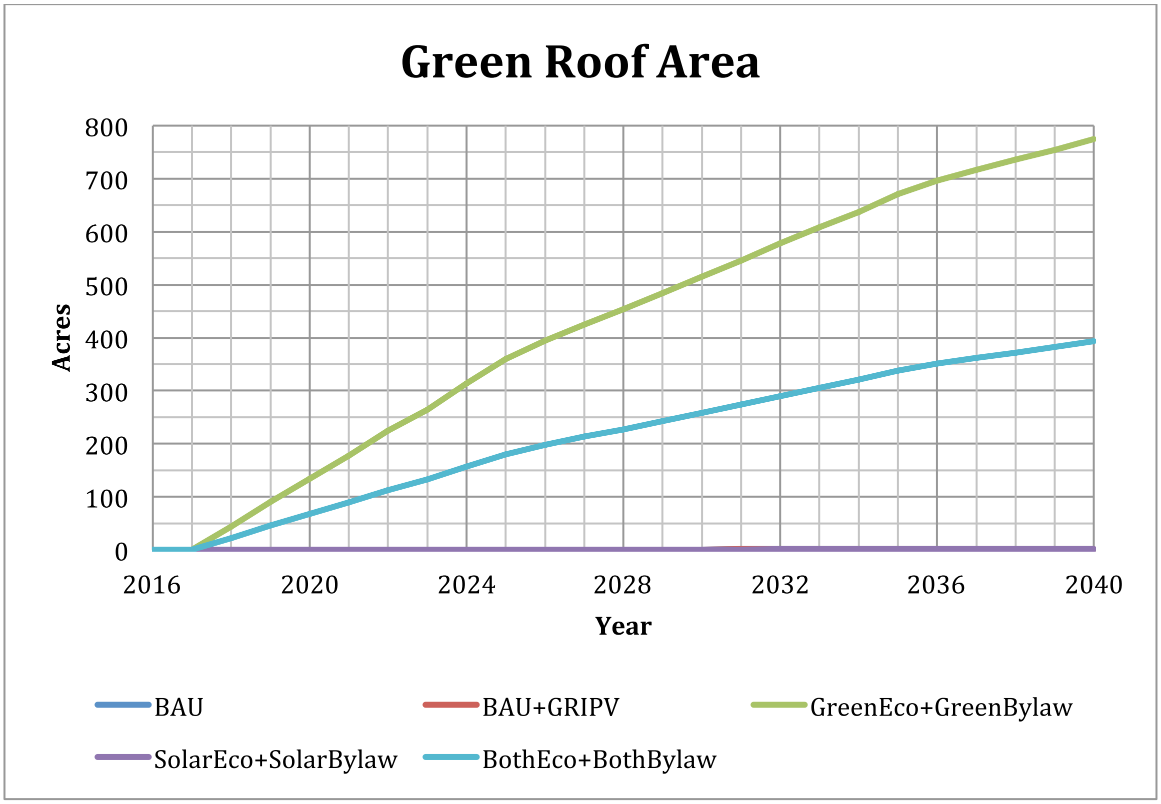


Figure 51: Green Roof Area Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

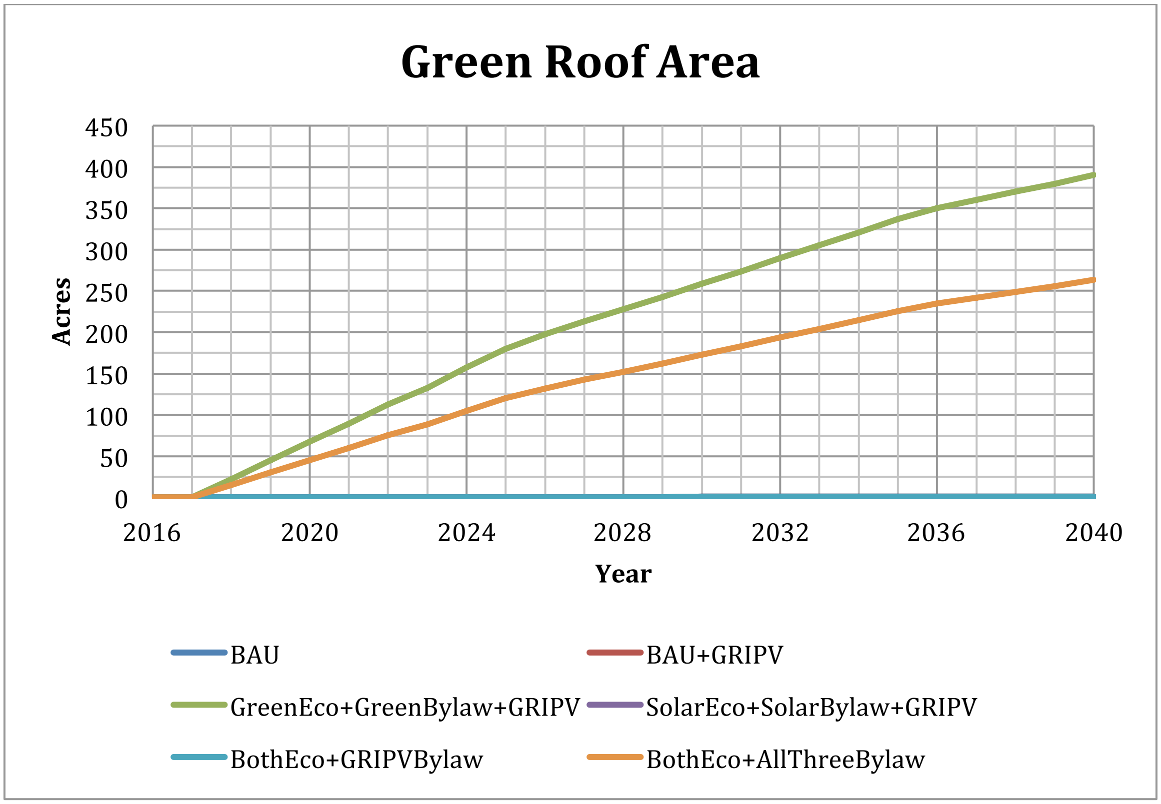


Figure 52: Green Roof Area Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.3 Solar Roof Area

The bylaw case study policy results with respect to solar PV/BIPV roof area are presented graphically in Figures 53 through 56. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the BAU or GRIPV-only scenarios; these graphs will instead be presented in Figures K5 and K6. Unlike the green roof bylaw market penetration results from the previous section, which gradually slowed down in later years the bylaw market shares for solar roofing showed consistently steady increasing trends throughout, indicating less policy resistance to such bylaws over time (most likely due to the solar roof market already being relatively well-established in Orlando). As shown in these graphs, solar roof market penetration is understandably at its highest with roofing bylaws that more specifically focus on the adoption of solar PV/BIPV roof systems, with solar roof area reaching as high as 1,384 acres in 2040 under the "SolarBylaw" scenario as opposed to 19.55 acres under the BAU scenario; although not as dramatic as the accelerated growth of the green roof market under similar policy conditions (most likely due to the solar roof market already being relatively well-established in Orlando), this increase was still nearly four times as much as the corresponding optimal increase in solar roof area from the original policy analysis (Table 27), indicating that the solar roofing industry also stands to gain considerably by focusing on solar roof adoption for new urban development as opposed to the retrofitting of pre-existing conventional roofs. Furthermore, it must be noted that all bylaw scenarios in which solar roofing was an available option also yielded significantly higher market penetration levels than that of the BAU scenario. For instance, the "AllThreeBylaw" scenario had all three alternative roof types as available options and was therefore the least stringent bylaw scenario for the adoption of any particular alternative roof option, but the solar roof market penetration under this scenario was still significantly higher than that of the BAU scenario (544 acres versus 19.55 acres).

On another note, like with the green roofing results from Section 6.3.1.2, it was observed that the offering of financial incentives for solar roofing resulted in a minor decrease in solar roof market penetration (e.g. 1,384 acres in 2040 under the "SolarBylaw" scenario versus 1,362 acres in 2040 under the "SolarEco+SolarBylaw" scenario), which may once again indicate a reduction in the feasibility of using financial incentives to support the effectively forced adoption of the alternative roofing type(s) specified in the bylaw requirements, especially as said bylaw requirements focus more specifically on a particular alternative roofing option and thus require financial support for higher levels of penetration. That said, although this minor decrease is greater than that of the solar roof market in terms of acreage, it must be noted that this decrease in solar roof area is also virtually negligible compared to the overall benefits relative to the BAU scenario. For instance, despite a decrease in 2040 solar roof area of roughly 22 acres between the "SolarBylaw" and "SolarEco+SolarBylaw" scenarios, the 2040 green roof area under the "SolarEco+SolarBylaw" scenario is still far greater than that of the BAU scenario, meaning that the overall market penetration benefits from solar roofing bylaws still outweigh any apparent drawback from the cost of offering financial support. Furthermore, there was a noticeable increase in solar roof market penetration with such financial incentives being offered in conjunction with roofing bylaws under "balanced" policy scenarios in which the green and solar roof markets were both targeted (e.g. "AllThreeBylaw" vs. "BothEco+AllThreeBylaw"), which may be due in part to the relative market maturity of solar roofing as opposed to green and GRIPV roofing. Nevertheless, it is still highly recommended for such financial incentives to focus on operational savings (e.g. discounts on electric bills for solar roof owners) where possible, thereby requiring less direct financial support from the government and/or from other private entities and in turn reducing or even eliminating any adverse feasibility impacts.

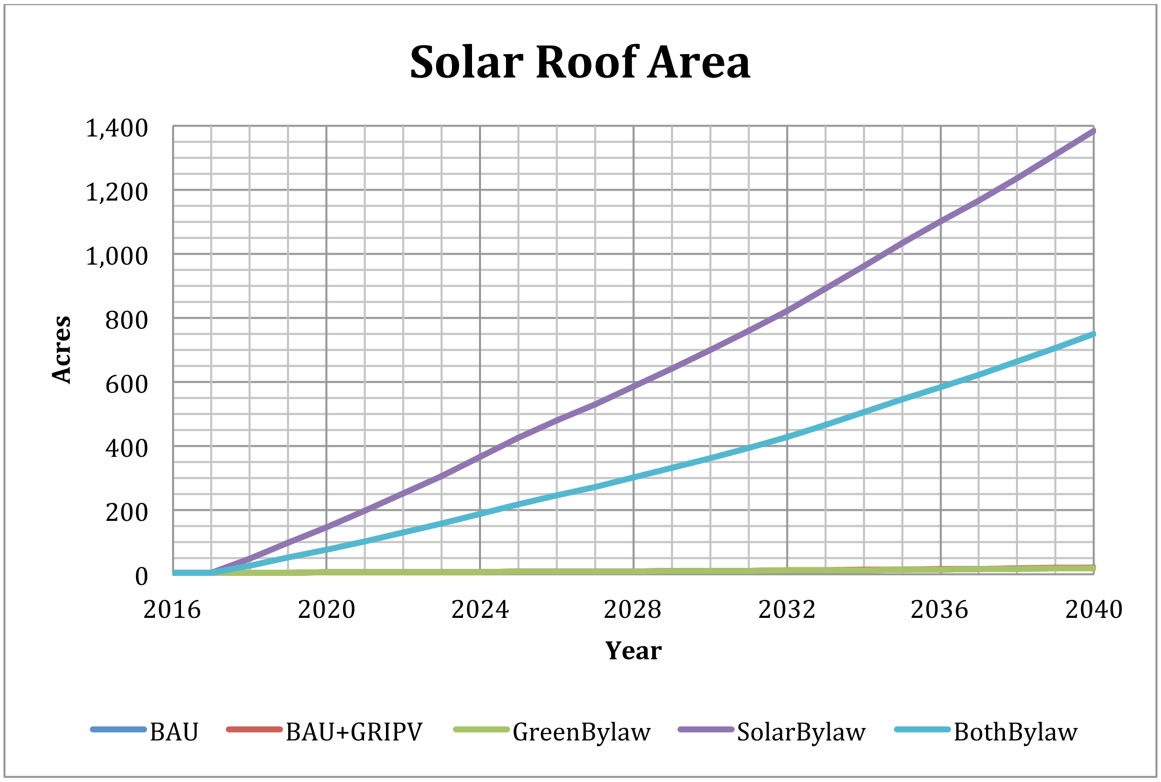


Figure 53: Solar Roof Area Case Study Policy Results – Bylaws Only

(No GRIPV Market)

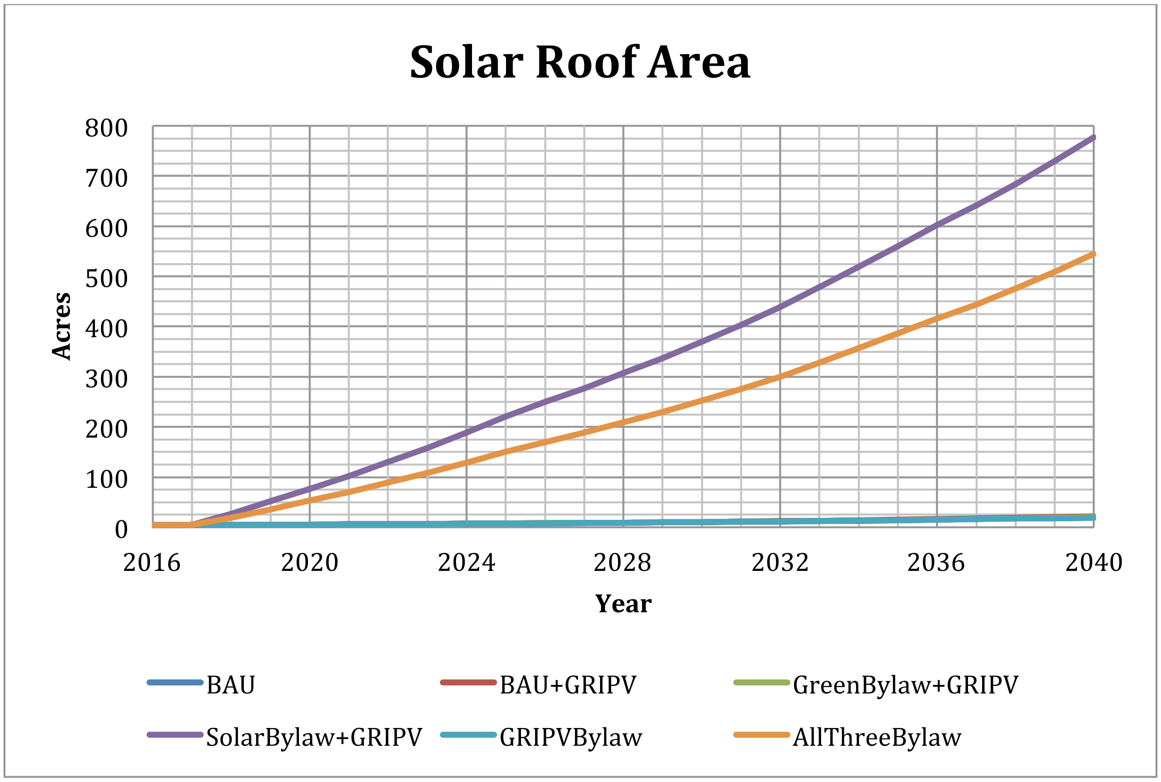


Figure 54: Solar Roof Area Case Study Policy Results – Bylaws Only

(GRIPV Included)

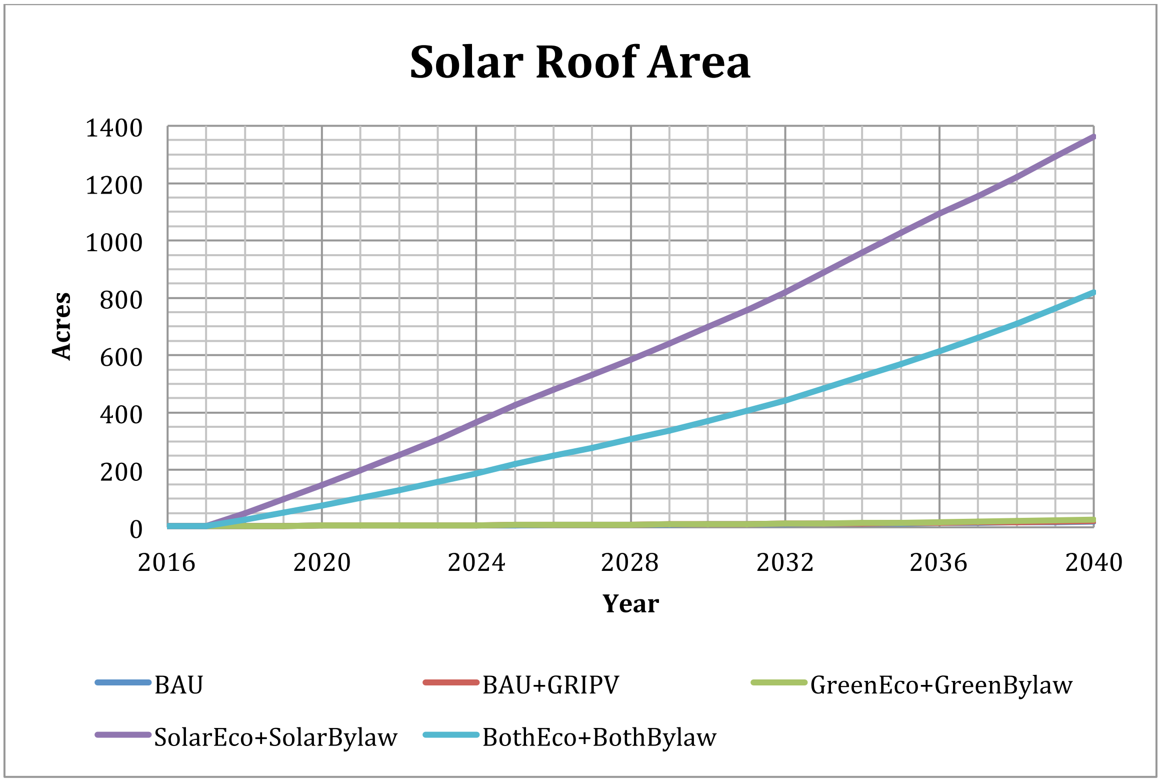


Figure 55: Solar Roof Area Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

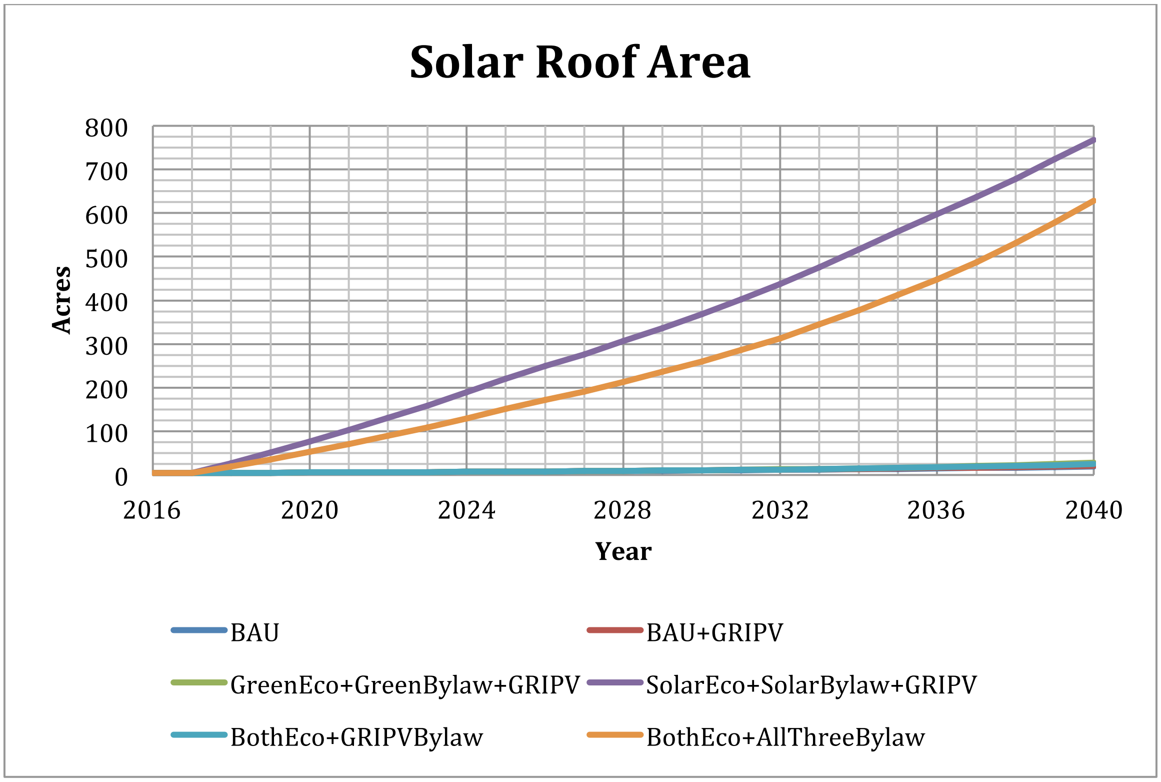


Figure 56: Solar Roof Area Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.4 GRIPV Roof Area

The bylaw case study policy results with respect to solar PV/BIPV roof area are presented graphically in Figures 57 and 58. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the graph for the GRIPV-only scenario; this graph will instead be presented in Figure K7. As previously observed in the regular policy results (Section 6.1.4), the bylaw results for GRIPV roofing once again tend to follow a trend most similar to the corresponding results for green roofing, except the market growth trends for GRIPV roofing are visibly less steady, indicating more sensitivity to the qualifying area randomizers (QARs) included in the formulation for bylaw-related adoption (meaning that the GRIPV market is more sensitive to bylaw criteria and requirements, the individual preferences of the owners of buildings covered under such bylaws, and other external bylaw-related factors). Additionally, as shown in Figures 57 and 58, GRIPV roof market penetration is understandably at its highest with roofing bylaws that more specifically focus on the adoption of GRIPV roof systems, with GRIPV roof area reaching as high as 659 acres in 2040 under the "GRIPVBylaw" scenario as opposed to roughly 0.5 acres under the BAU+GRIPV scenario; this is the most dramatic of the accelerated growth rates out of all of the considered alternative roof markets under similar policy conditions (most likely owing to the fact that the GRIPV roof industry is currently the least developed out of the three alternative roof markets analyzed in this study), and was also far greater than the optimal increase in GRIPV roof area from the original policy analysis (Table 27), indicating that the GRIPV roofing industry has the most to gain from policies that focus on GRIPV roof adoption for new urban development as opposed to the retrofitting of pre-existing conventional roofs. Furthermore, it must be noted that all bylaw scenarios in which GRIPV roofing was an available option also yielded significantly higher market penetration levels than that of the BAU scenario. For instance, the "AllThreeBylaw" scenario had all three alternative roof types as available options and was therefore the least stringent bylaw scenario for the adoption of any particular alternative roof option, but the GRIPV roof market penetration under this scenario was still significantly higher than that of the BAU scenario (220 acres versus 0.5 acres). It is interesting to note, however, that for the adoption of either green roofing or solar roofing to be required via bylaws with the GRIPV market taken into account (the "GreenBylaw+GRIPV" and "SolarBylaw+GRIPV" scenarios, respectively) led to virtually identical market penetration rates for GRIPV roofing at approximately 330 acres and 328 acres respectively in the year 2040.

It was also observed that, unlike with the green and solar roofing results (Sections 6.3.1.3 and 6.3.1.4, respectively), the minor decrease in GRIPV roof market penetration was not evident with unit-based financial incentives offered for solar roofing, indicating that financial support for GRIPV roofing is most feasible when offered on a per-kWh basis rather than a per-acre basis. Even when incentives are offered on a per-acre basis, however, the resulting decrease in GRIPV roof area is still virtually negligible compared to the overall benefits relative to the GRIPV-only scenario. For instance, despite a decrease in 2040 GRIPV roof area of 2.4 acres between the "GreenBylaw+GRIPV" and "GreenEco+GreenBylaw+GRIPV" scenarios, the 2040 GRIPV roof area under the "GreenEco+GreenBylaw+GRIPV" scenario is still far greater than that of the GRIPV-only scenario, meaning that the overall market penetration benefits from GRIPV roofing bylaws still outweigh any drawback from the cost of offering financial support. That said, it is still highly recommended to make use of financial incentives that focus on operational savings (e.g. discounts on electric bills for solar roof owners) wherever possible, thereby requiring less direct financial support from the government and/or from other private entities and in turn reducing or even eliminating any adverse feasibility impacts.

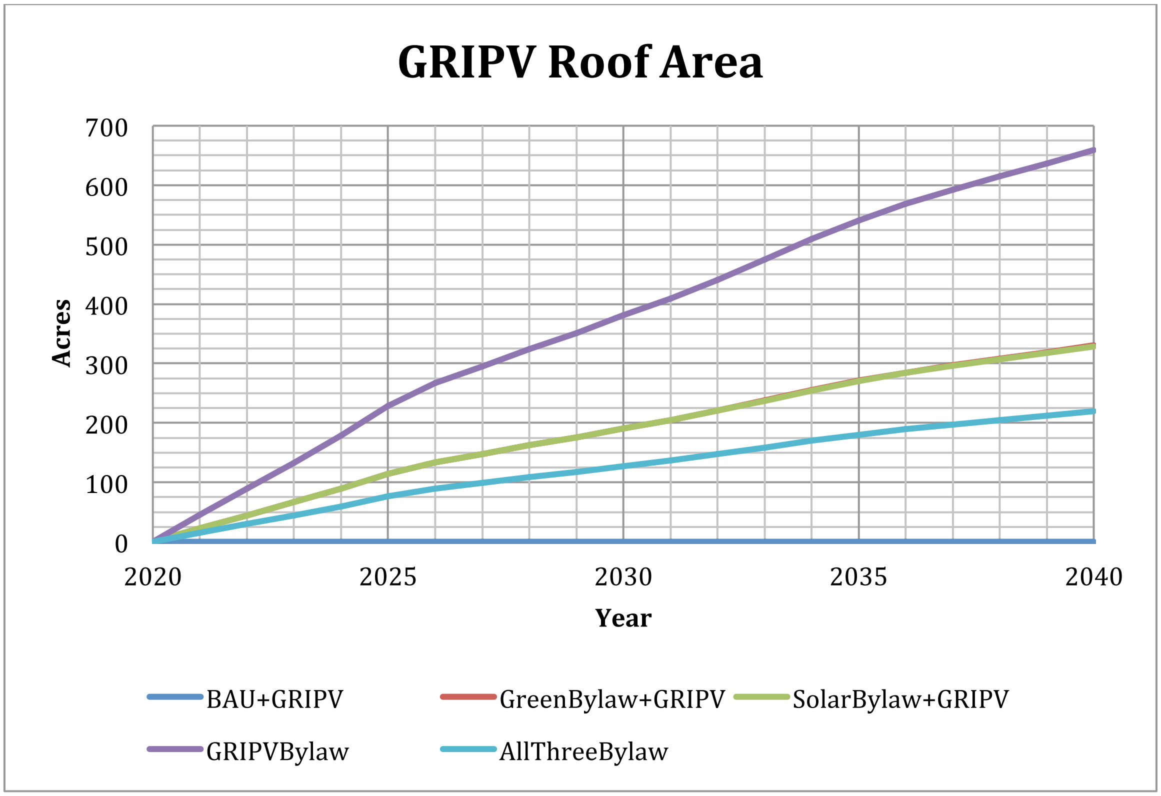


Figure 57: GRIPV Roof Area Case Study Policy Results – Bylaws Only

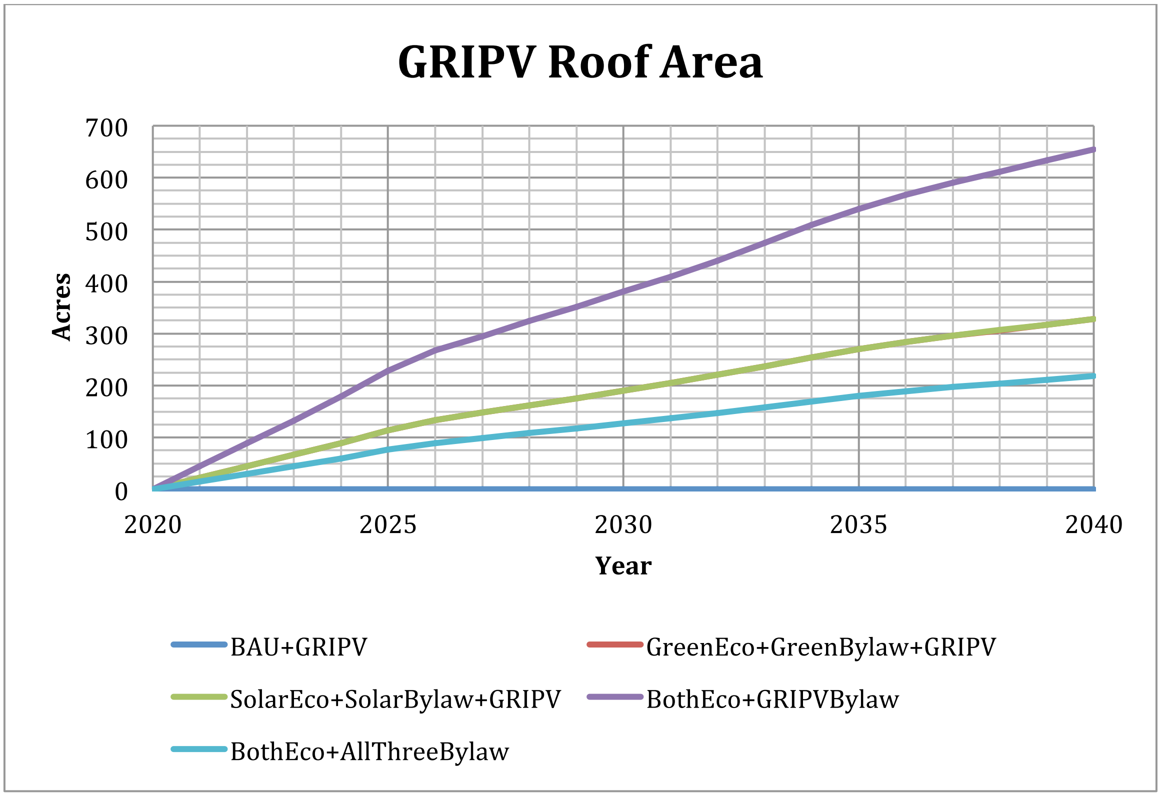


Figure 58: GRIPV Roof Area Case Study Policy Results – Bylaws & Financial Incentives

6.3.1.5 Total Annual Runoff Depth

The bylaw case study policy results with respect to urban runoff are presented in Figures 59 through 62. The non-bylaw results will not be shown graphically in this section because the corresponding graphs do not show any visibly significant change in the graphical trends in the results; these graphs will instead be presented in Figures K8 and K9. Even under the relatively lax bylaw criteria specified in this study (required for buildings with roof areas of 100,000 ft^2 or larger), urban runoff could potentially be reduced by up to 0.16 inches under the “GreenBylaw” and “GreenEco+GreenBylaw” scenarios, with comparable reductions of approximately 0.13 inches in the “GRIPVBylaw” and “BothEco+GRIPVBylaw” scenarios and approximately 0.10

inches in the “AllThreeBylaw” and “BothEco+AllThreeBylaw” scenarios. All of these results are significant improvements over the regular policy results (Section 6.1.5), but are all still very small in terms of overall progress, owing primarily to the fact that even the highest observed green and GRIPV roof market penetration levels are still far smaller than the corresponding conventional roof acreage. Nevertheless, this finding still serves to highlight the fact that the high rainfall retention capacities of green and GRIPV roofing make them the best alternative roofing options for reducing urban runoff, while the bylaw results clearly demonstrate the potential effectiveness of alternative roofing adoption strategies for new buildings in addition to the retrofitting of pre-existing buildings. Furthermore, since all bylaw scenarios essentially equate to a reduction in the initial increase in conventional roof area in any given year, these findings also provide some degree of insight into the potential to more significantly reduce urban runoff by reducing the need for conventional building materials and (to a greater degree) by reducing the overall need for additional land development through any of the land-efficiency policies previously discussed in Section 6.1.1 (renovating and/or rebuilding old construction instead of clearing undeveloped land space, developing and adjusting socioeconomic systems to reduce the required land footprint for certain types of buildings, etc.). Finally, it is worth noting that the use of financial support in conjunction with alternative roofing bylaws had no significant effect on the runoff reductions from the application of such bylaws, meaning that to invest in such incentives to provide support for bylaw implementation would have little to no long-term impact on urban runoff, but this also means that such support can still be provided to assist building owners with alternative roofing costs whenever possible without any adverse impacts.

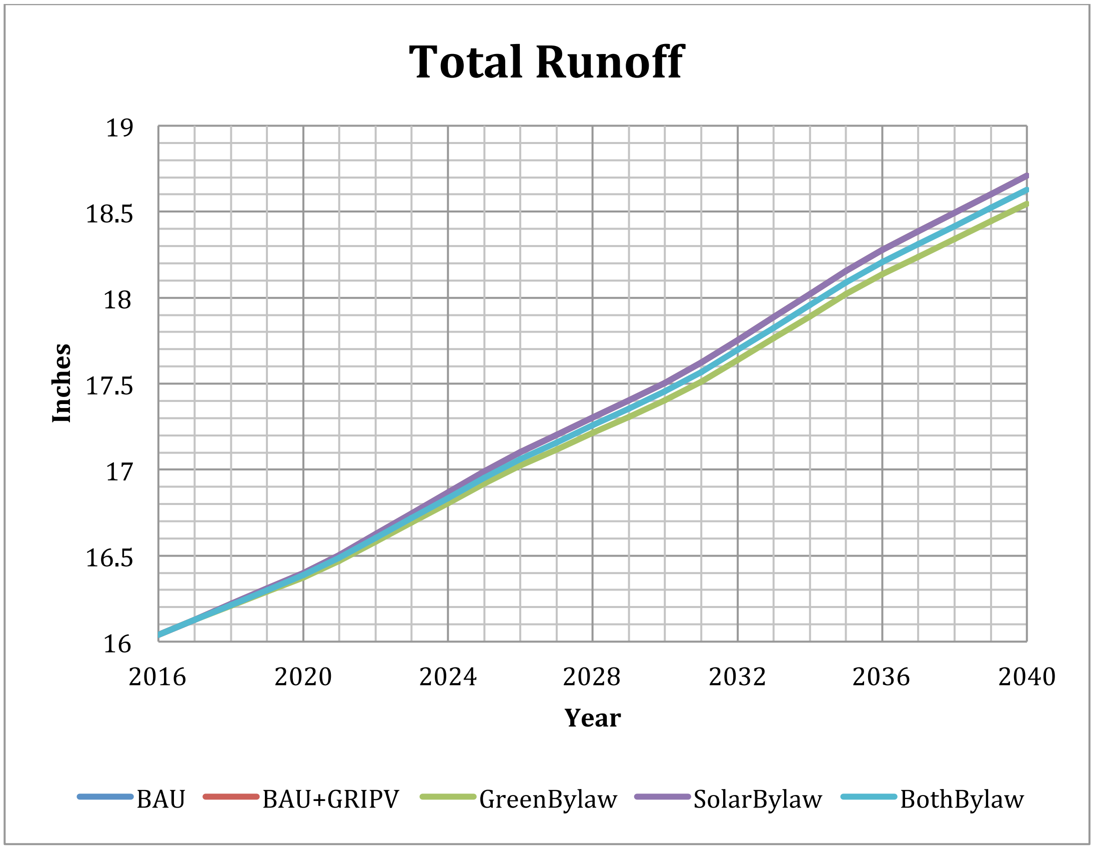


Figure 59: Total Runoff Case Study Policy Results – Bylaws Only

(No GRIPV Market)

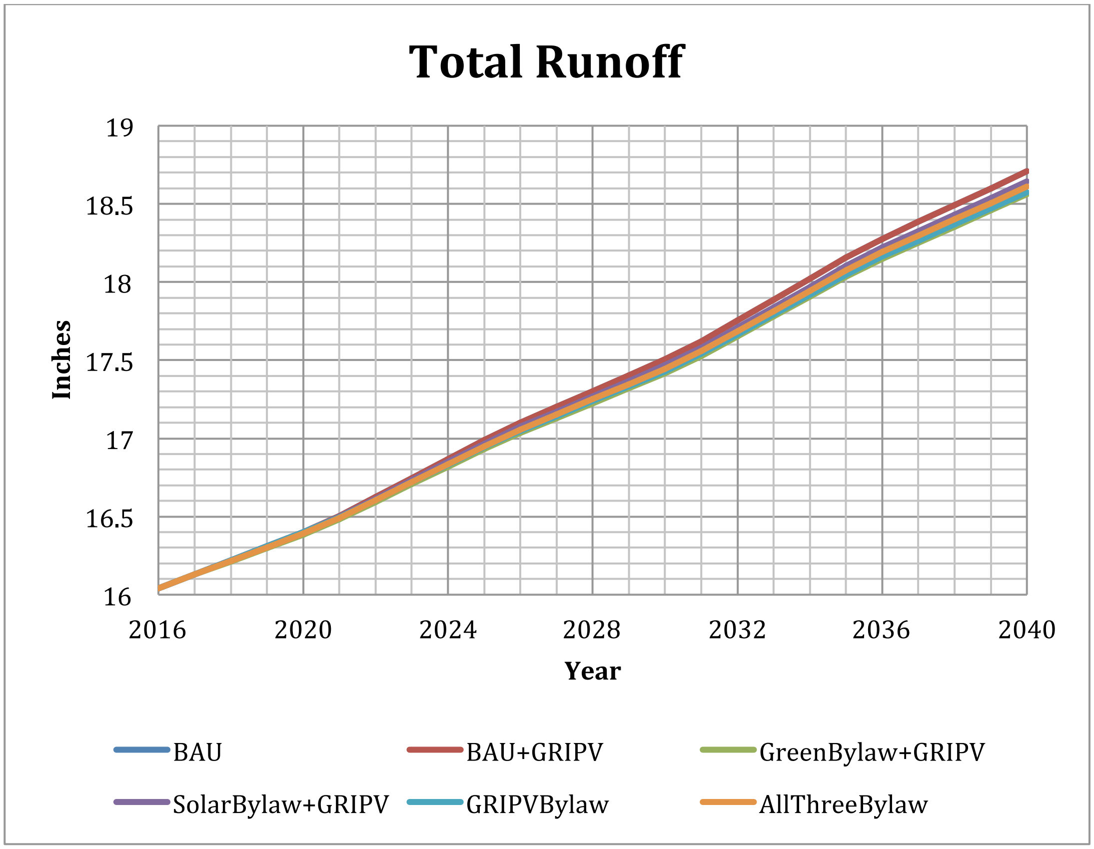


Figure 60: Total Runoff Case Study Policy Results – Bylaws Only

(GRIPV Included)

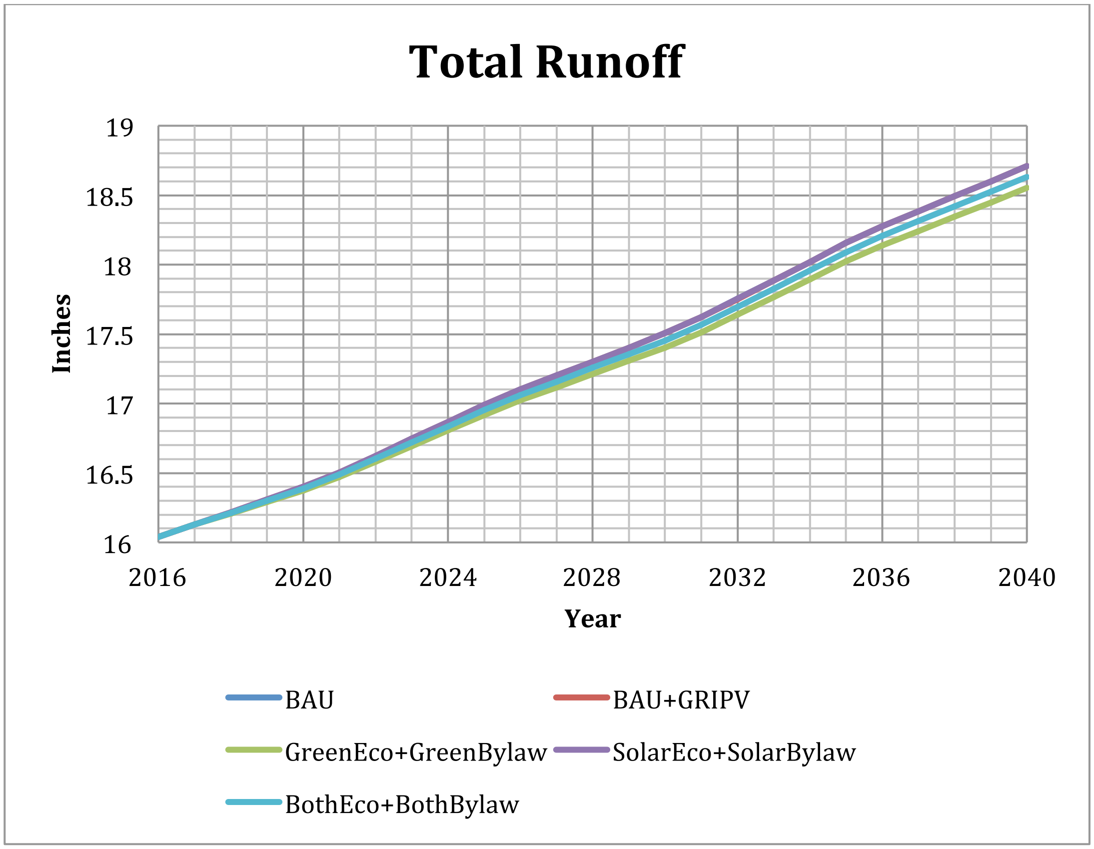


Figure 61: Total Runoff Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

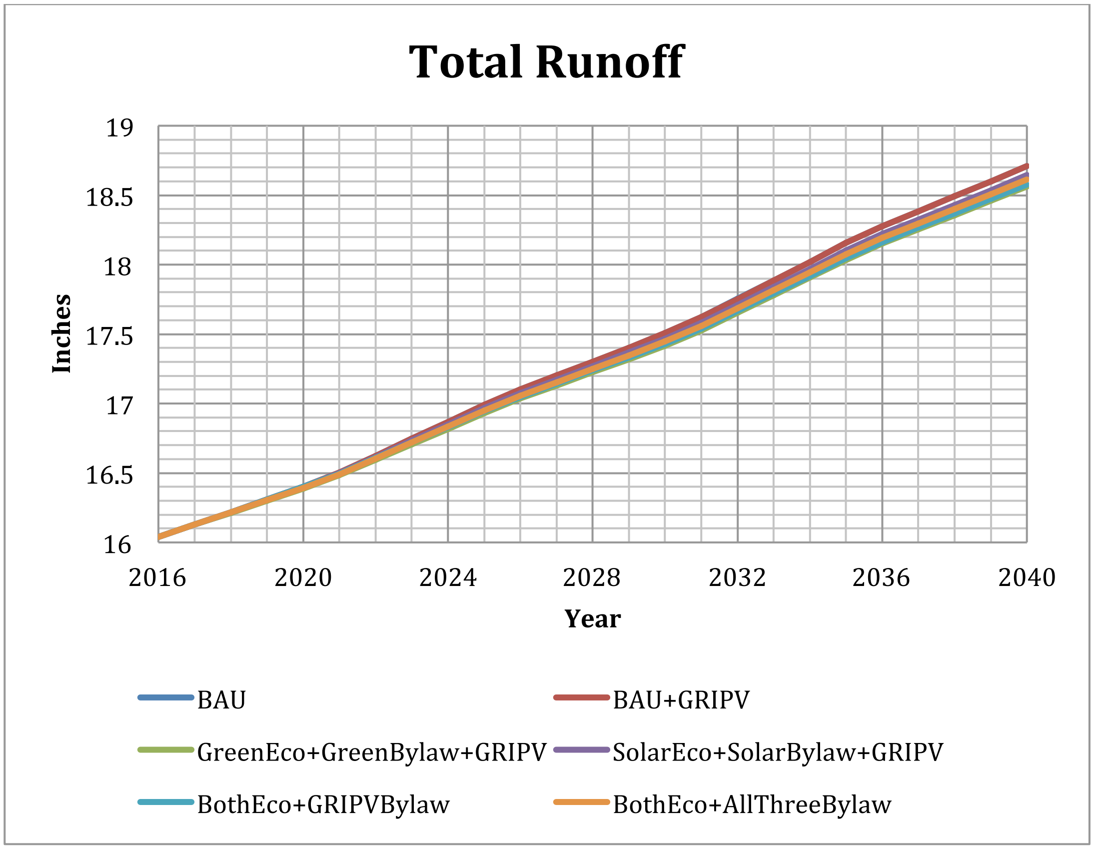


Figure 62: Total Runoff Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.6 Air Temperature Anomaly

The bylaw case study policy results with respect to air temperature anomaly are presented graphically in Figures 63 through 66. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the graph for the GRIPV-only scenario; these graphs will instead be presented in Figures K10 and K11. Although the long-term case study results indicated a maximum air temperature anomaly reduction of only about 0.023^0F (a 2% decrease relative to 2040 BAU results) whereas the average historical anomaly is far greater at 1^0F (Table 4), this reduction is significantly greater than the maximum reduction previously observed in the "Solar2+GRIPV" scenario of the original policy analysis (Section 6.1.6). Moreover, although the "Solar2+GRIPV" scenario was the optimal scenario in the regular policy analysis in terms of the UHI effect (Section 6.1.6), the corresponding optimal case study policy scenario in this regard was the "GreenBylaw" scenario with comparable air temperature anomaly reductions of approximately 0.02^0F in all other bylaw scenarios, which clearly highlights the potential of all alternative roofing options (esp. green and GRIPV roofing, which tended to yield greater reductions when targeted in any given bylaw scenario) to contribute more significantly to reductions in the UHI effect in the future at sufficiently high market penetration levels, as well as the potential benefits of encouraging alternative roof market penetration for newly constructed roofing in addition to the more conventional "retrofitting" adoption strategies and/or reducing the need for conventional building materials and (to a potentially greater degree) by reducing the overall need for additional land development through any of the land-efficiency policies previously discussed in Section 6.1.1. Lastly, although current governmental subsidy levels were found to be unlikely to have any significant effect in this regard, they and other governmental and/or private financial incentives can still provide enough support to make the implementation of such bylaws more realistically feasible.

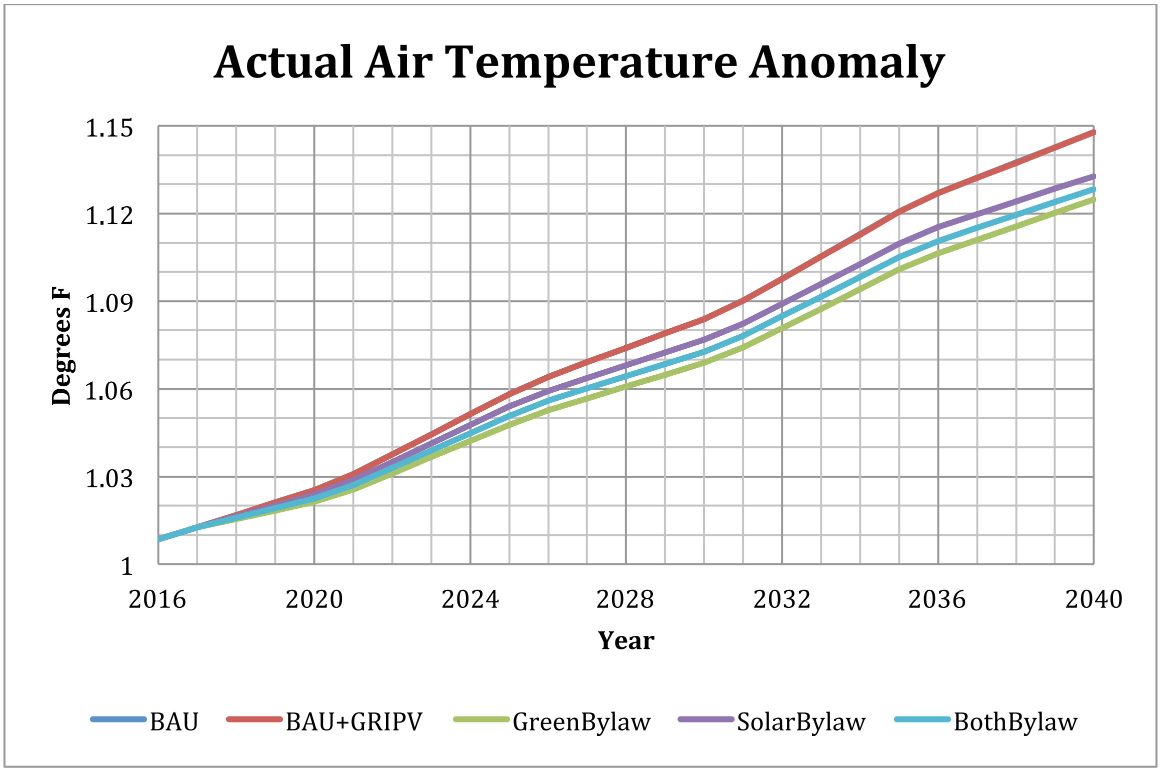


Figure 63: Air Temperature Anomaly Case Study Policy Results – Bylaws Only

(No GRIPV Market)

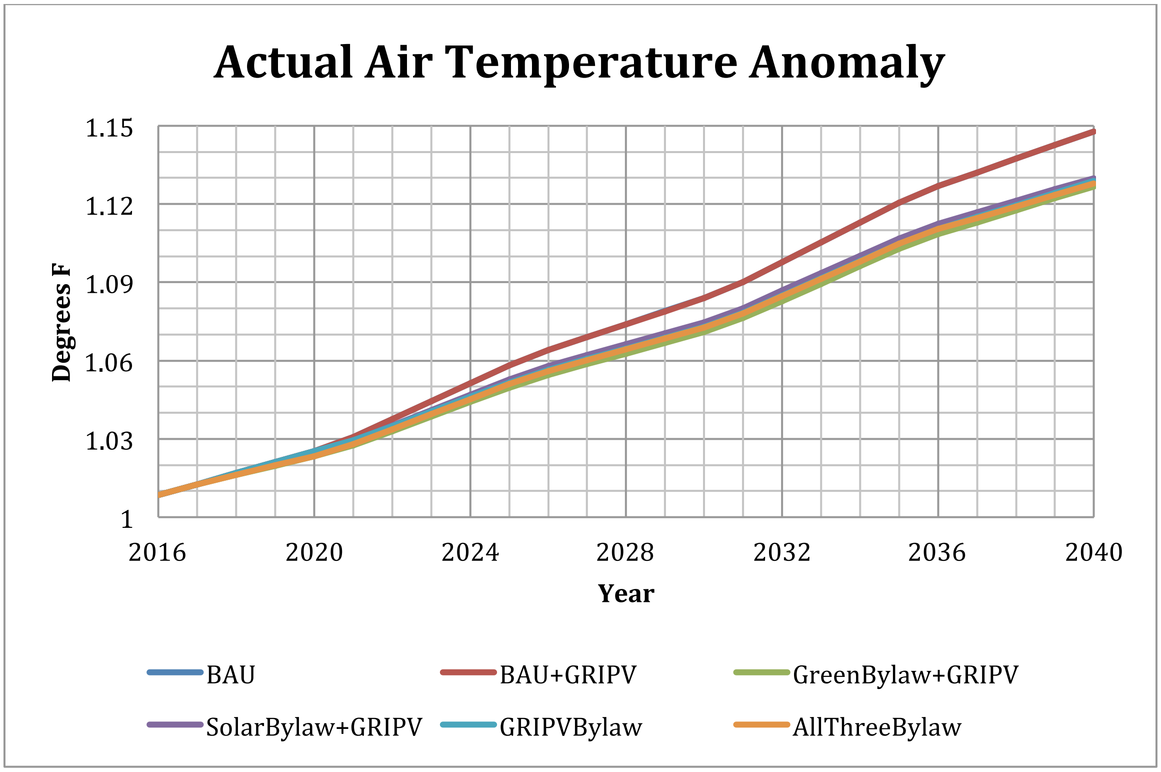


Figure 64: Air Temperature Anomaly Case Study Policy Results – Bylaws Only

(GRIPV Included)

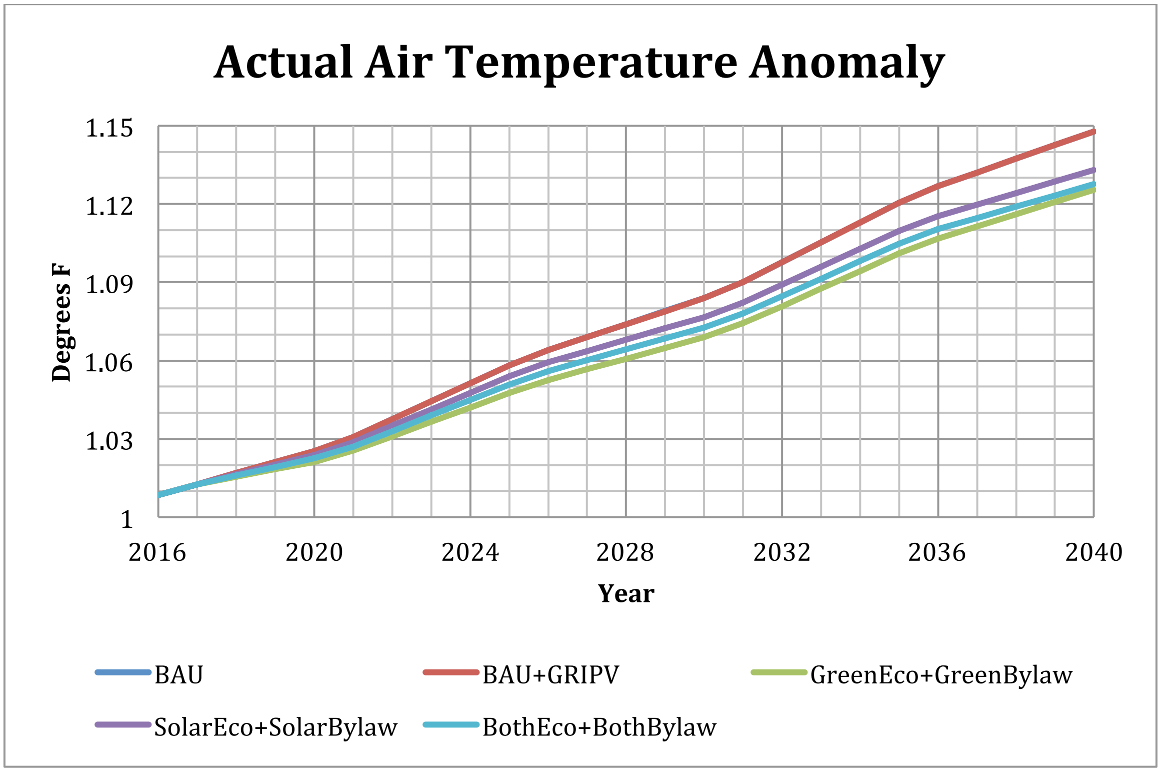


Figure 65: Air Temperature Anomaly Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

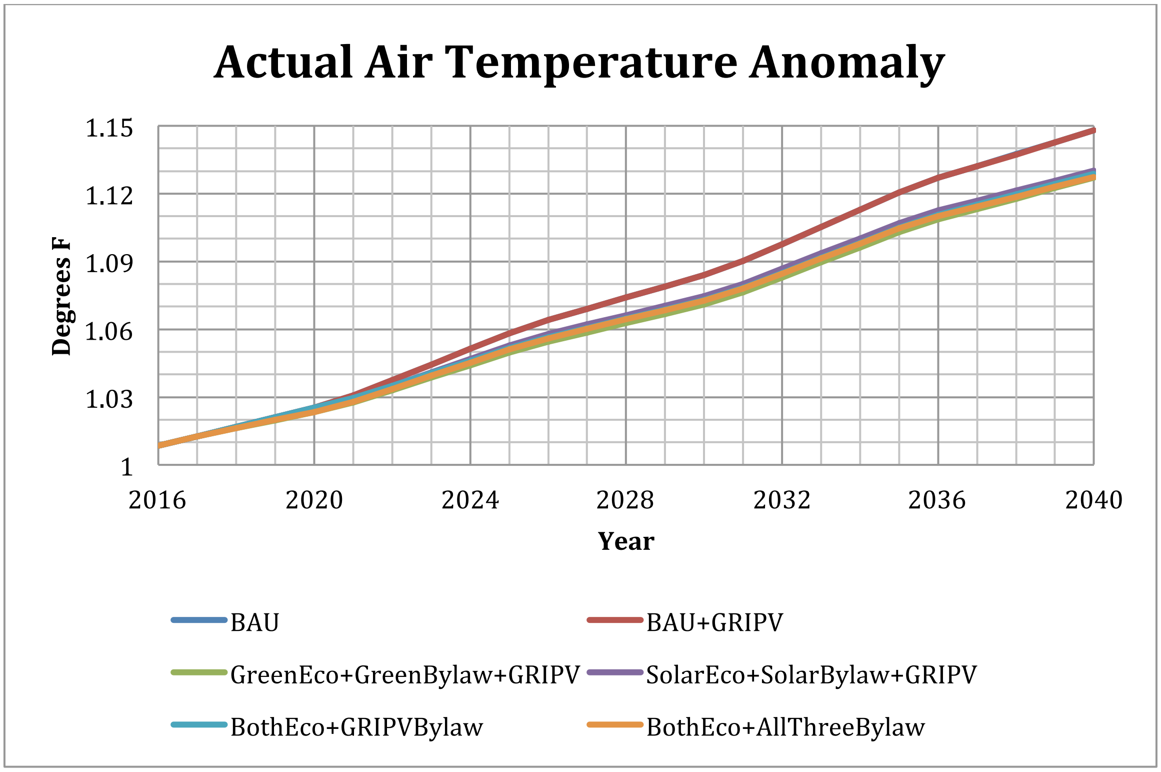


Figure 66: Air Temperature Anomaly Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.7 Energy Goal Progress

The bylaw case study policy results with respect to the established 2040 energy savings goal are presented graphically in Figures 67 through 70. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the corresponding graphs for the BAU and GRIPV-only scenario; these graphs will instead be presented in Figures K12 and K13. Like the corresponding regular policy results (Section 6.1.7), the most significant increases in energy savings were observed in scenarios where adoption bylaws emphasized the solar and/or GRIPV roof markets to at least some degree, with the corresponding 2040 energy savings contributions in such scenarios ranging from 6.77% (the "GreenBylaw+GRIPV" scenario) to 45.16% (the "SolarBylaw" scenario) of goal progress by the year 2040, primarily because solar and GRIPV roofing both actively generate energy in addition to their more passive energy savings from reduced cooling demand, whereas green roofing alone cannot actively produce energy. However, it is immediately apparent from these results that even the least stringent roofing bylaws in this regard can contribute far more to the established energy savings goal than what was previously possible in the regular policy results (e.g. 24.56% in the "BothEco+AllThreeBylaw" scenario vs. 4.13% in the "Solar2+GRIPV" scenario), once again demonstrating the effectiveness of including new construction in alternative roofing adoption strategies. Lastly, unlike in previous impact categories, unit-based financial incentives were found to increase 2040 to a certain degree in most bylaw scenarios (e.g. 24.56% in the "BothEco+AllThreeBylaw" scenario vs. 21.83% in the "AllThreeBylaw" scenario); the only exception in this regard was in the "SolarBylaw" and "SolarEco+SolarBylaw" scenarios with goal progress levels of 45.16% and 44.46% respectively, but the difference between these two scenarios was relatively small at only 0.70%. In short, to offer such incentives (via direct subsidies or via "indirect" utility discounts) is unlikely to have any adverse effect on the overall energy savings from the alternative roofing industry and is instead more likely to add a slight boost in this regard, all while still providing enough support to make the implementation of such bylaws more realistically feasible for building owners.

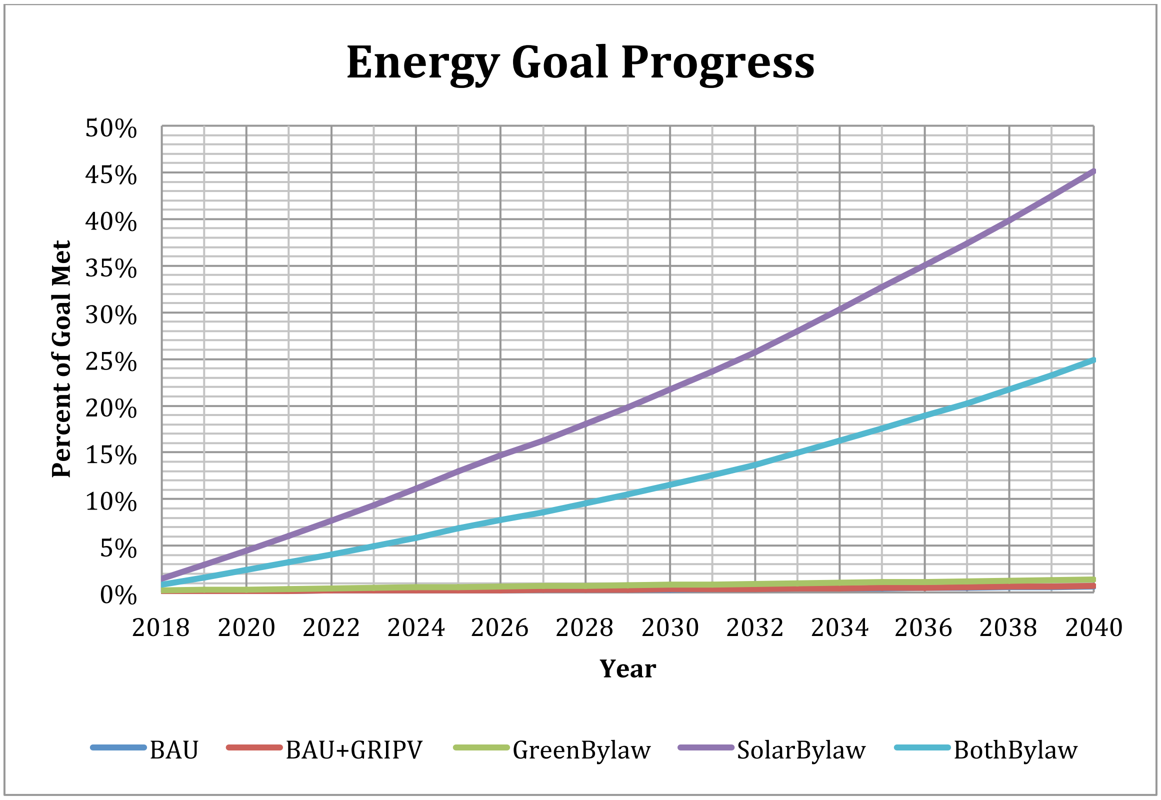


Figure 67: Energy Goal Progress Case Study Policy Results – Bylaws Only

(No GRIPV Market)

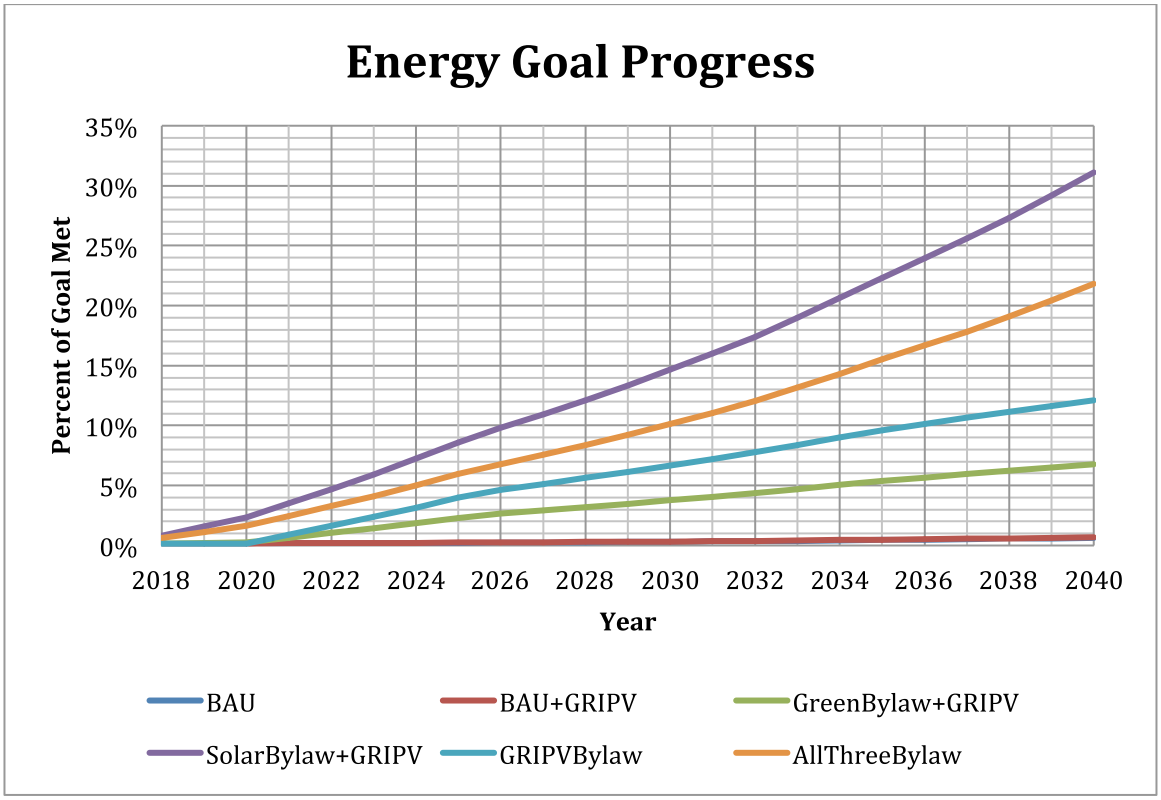


Figure 68: Energy Goal Progress Case Study Policy Results – Bylaws Only

(GRIPV Included)

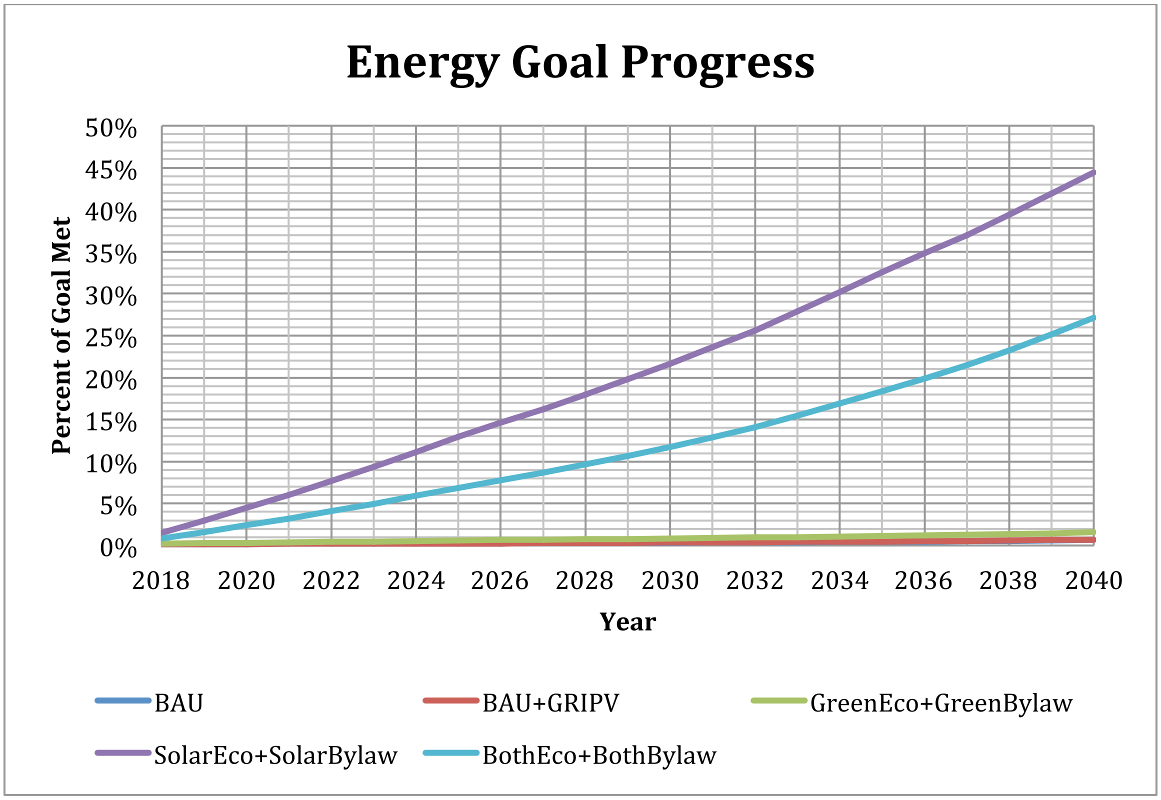


Figure 69: Energy Goal Progress Case Study Policy Results – Bylaws & Financial Incentives (No GRIPV Market)

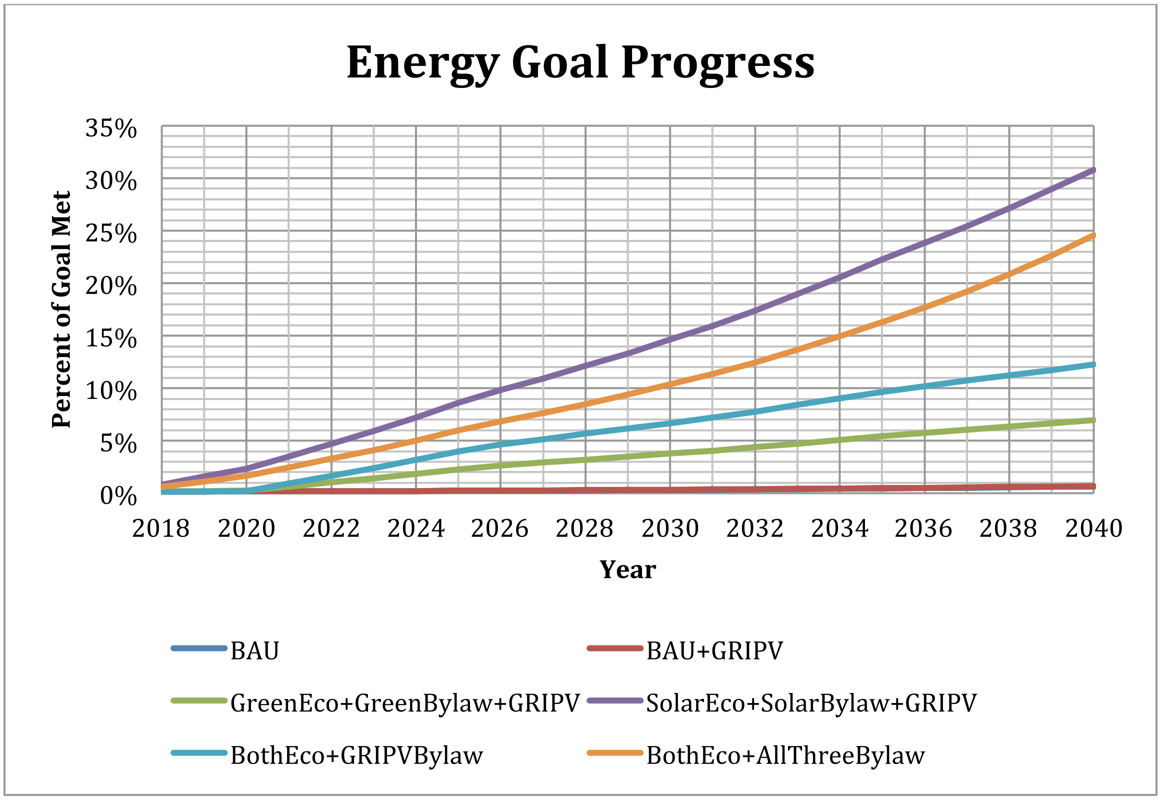


Figure 70: Energy Goal Progress Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.1.8 GHG Goal Progress

The bylaw case study policy results with respect to the established 2040 GHG emission reduction goal are presented graphically in Figures 71 through 74. The non-bylaw results will not be presented in this section because none of them display any significant graphical change relative to the corresponding graphs for the BAU and GRIPV-only scenario; these graphs will instead be presented in Figures K14 and K15. Like the corresponding regular policy results (Section 6.1.8), the most significant increases in energy savings were observed in scenarios where adoption bylaws emphasized the solar and/or GRIPV roof markets to at least some degree, with the corresponding 2040 GHG emission savings contributions in such scenarios ranging from 0.62% (the “GreenBylaw+GRIPV” scenario) to 3.82% (the “SolarBylaw” scenario) of goal progress by the year 2040, primarily because solar and GRIPV roofing both actively generate energy in addition to their more passive energy savings from reduced cooling demand, whereas green roofing alone cannot actively produce energy. However, it is immediately apparent from these results that even the least stringent roofing bylaws in this regard can contribute far more to the established GHG savings goal than what was previously possible in the regular policy results (e.g. 2.11% in the “BothEco+AllThreeBylaw” scenario vs. 0.35% in the “Solar2+GRIPV” scenario), once again demonstrating the effectiveness of including new construction in alternative roofing adoption strategies. Lastly, unlike in previous impact categories, unit-based financial incentives were found to increase 2040 to a certain degree in most bylaw scenarios (e.g. 2.11% in the “BothEco+AllThreeBylaw” scenario vs. 1.88% in the “AllThreeBylaw” scenario); the only exception in this regard was in the “SolarBylaw” and “SolarEco+SolarBylaw” scenarios with goal progress levels of 3.82% and 3.77% respectively, but the difference between these two scenarios was relatively small at only 0.05%. In short, to offer such incentives (via direct subsidies or via “indirect” utility discounts) is unlikely to have any adverse effect on the overall GHG emission savings from the alternative roofing industry and is instead more likely to add a slight boost in this regard, all while still providing enough support to make the implementation of such bylaws more realistically feasible for building owners.

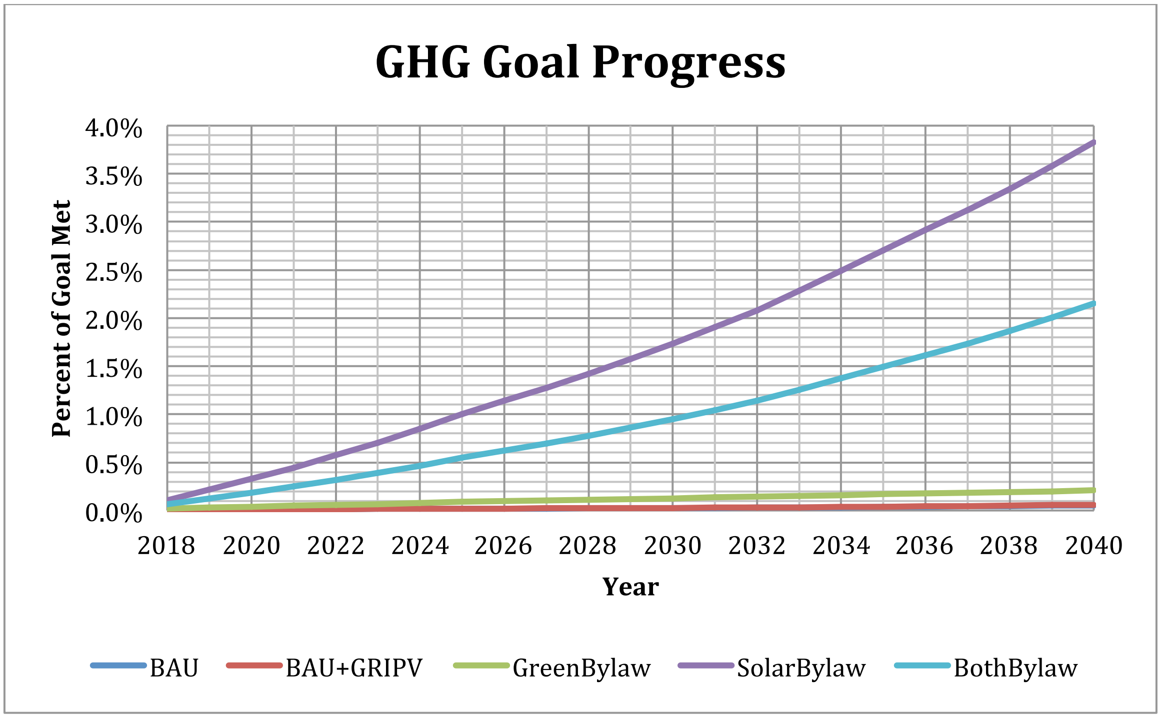


Figure 71: GHG Goal Progress Case Study Policy Results – Bylaws Only

(No GRIPV Market)

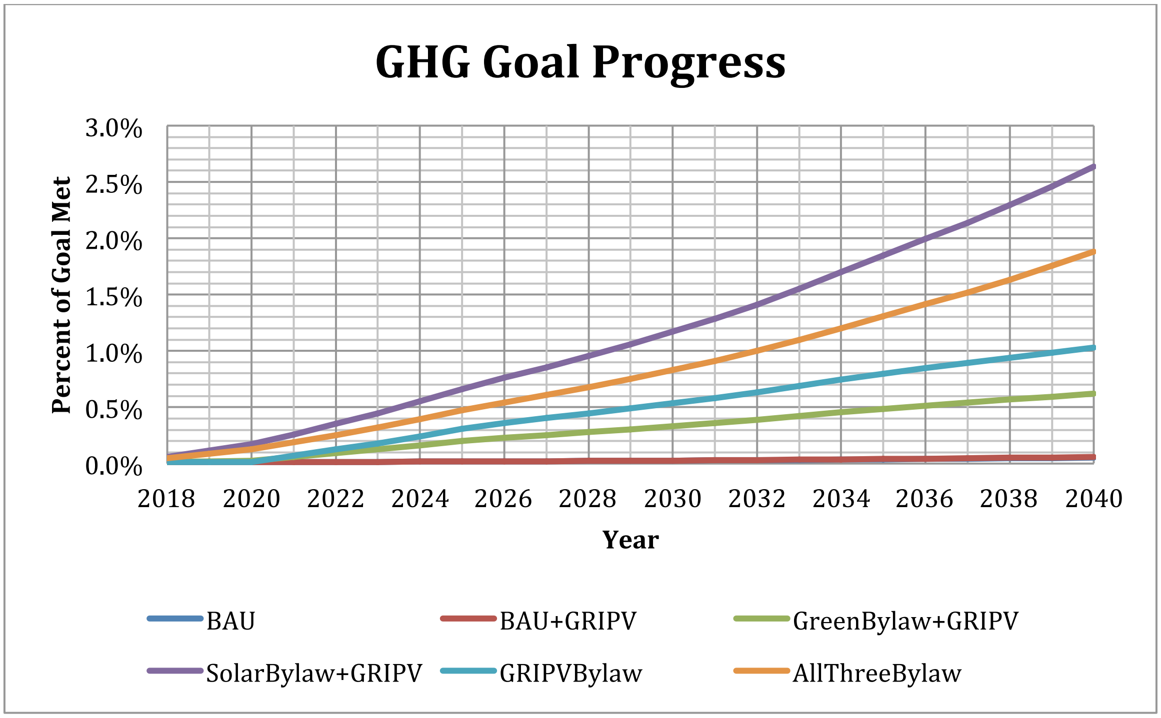


Figure 72: GHG Goal Progress Case Study Policy Results – Bylaws Only

(GRIPV Included)

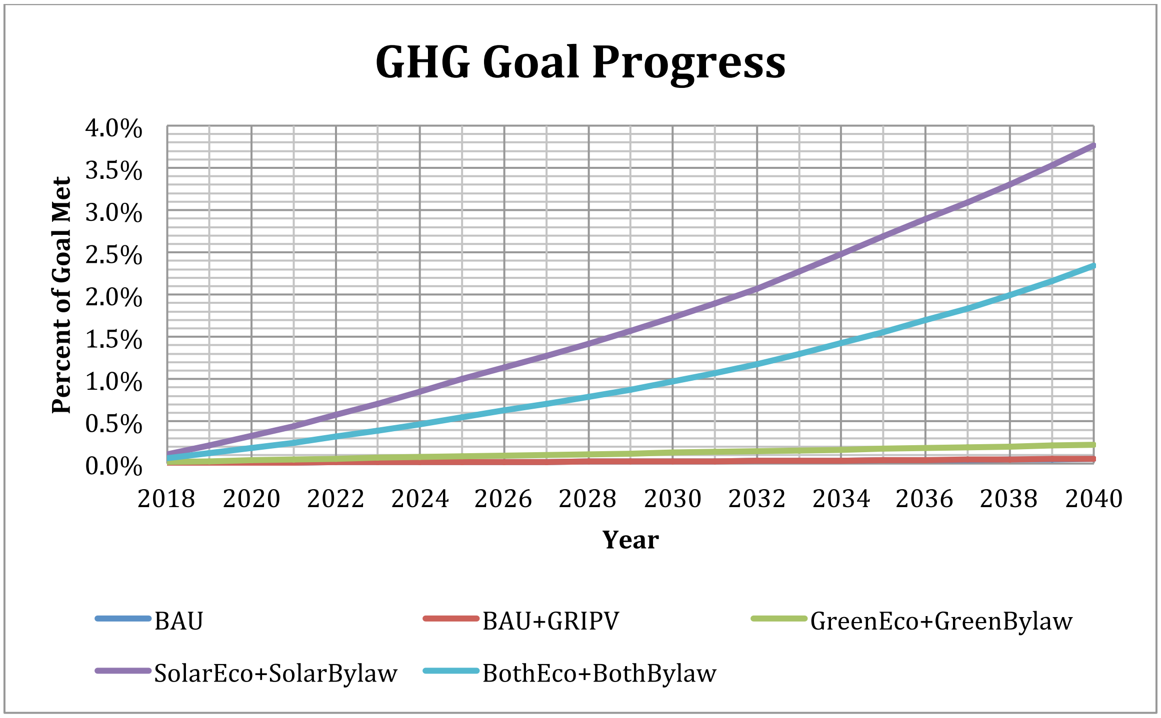


Figure 73: GHG Goal Progress Case Study Policy Results – Bylaws & Financial Incentives

(No GRIPV Market)

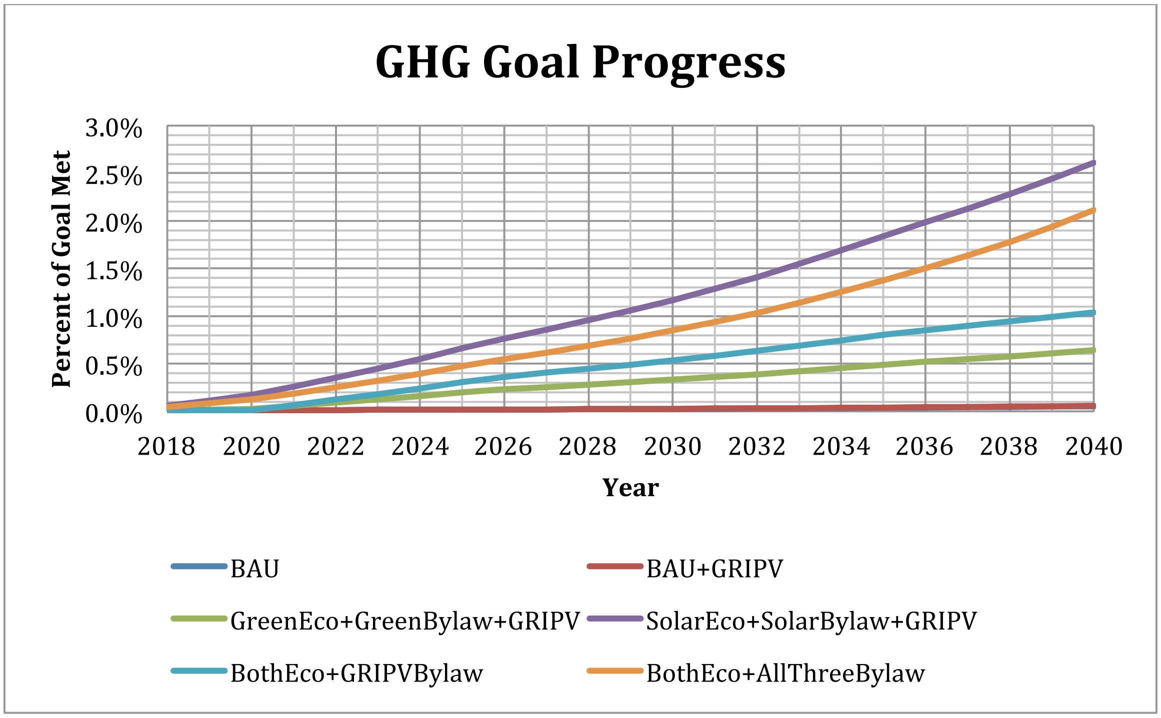


Figure 74: GHG Goal Progress Case Study Policy Results – Bylaws & Financial Incentives (GRIPV Included)

6.3.2 Case Study Uncertainty Results

In order to gain additional insight into the inherent uncertainty of the above-cited case study results, an additional uncertainty analysis has been simulated in this study under mostly BAU and GRIPV-only simulation conditions except for the introduction of varying degrees of possible bylaw market penetration ("Bylaw Switch" parameters ranging from 0 to 1, including GRIPV roofing bylaws where applicable) as simulated in the case study results, as well as probability distributions for economic incentives based on actual economic policies in other parts of the world (Appendix H). For this purpose, separate graphs and discussions will be provided for each output variable in Sections 6.3.2.1 through 6.3.2.8, and histograms corresponding to each set of uncertainty results will be provided in Appendix K.

6.3.2.1 Conventional Roof Area

The case study uncertainty results with respect to green roof area are presented graphically in Figures 75 and 76. These graphs and the corresponding 2040 histograms (Figure K18) show that the majority of the Monte Carlo simulation runs resulted in 2040 conventional roof areas between 30,700 acres and 32,540 acres (all less than the 32,941 acres predicted in the BAU scenario) with potential to reach as low as 27,480 acres, whereas the corresponding regular uncertainty results (Section 6.2.1) had a clear majority of 2040 values at 32,540 acres or higher. These histogram results and the uncertainty distribution graphs in this section and in Section 6.2.1 both demonstrate a clear increase in possible alternative roof market penetration levels when case study probability distributions were considered, especially with the possible introduction of alternative roofing bylaws, which have consistently shown in Section 6.3.1 to have the greatest impact on alternative roof market penetration due to their direct emphasis on new roofing construction as opposed to the "retrofitting" of pre-existing construction. It must also be noted that the fraction of new development selected for consideration in this study for alternative roofing bylaws ("Large Dev Fraction"), which was estimated based on the fraction of new roofing construction for roof areas of 100,000 ft^2 or larger (EIA 2016c), is less stringent than what most real-world green roof bylaws (Plant Connection, Inc. 2017), making it possible to further reduce these market shares if more stringent bylaws (e.g. smaller minimum areas) are feasible.

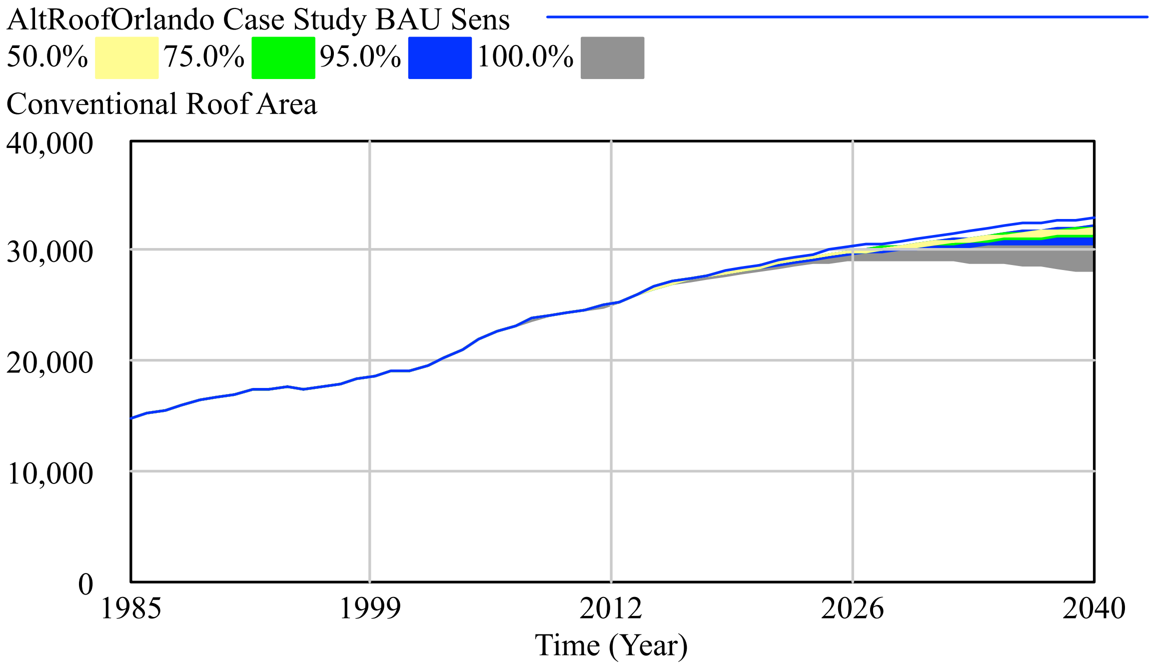


Figure 75: Conventional Roof Area Case Study Uncertainty Graph (No GRIPV Market)

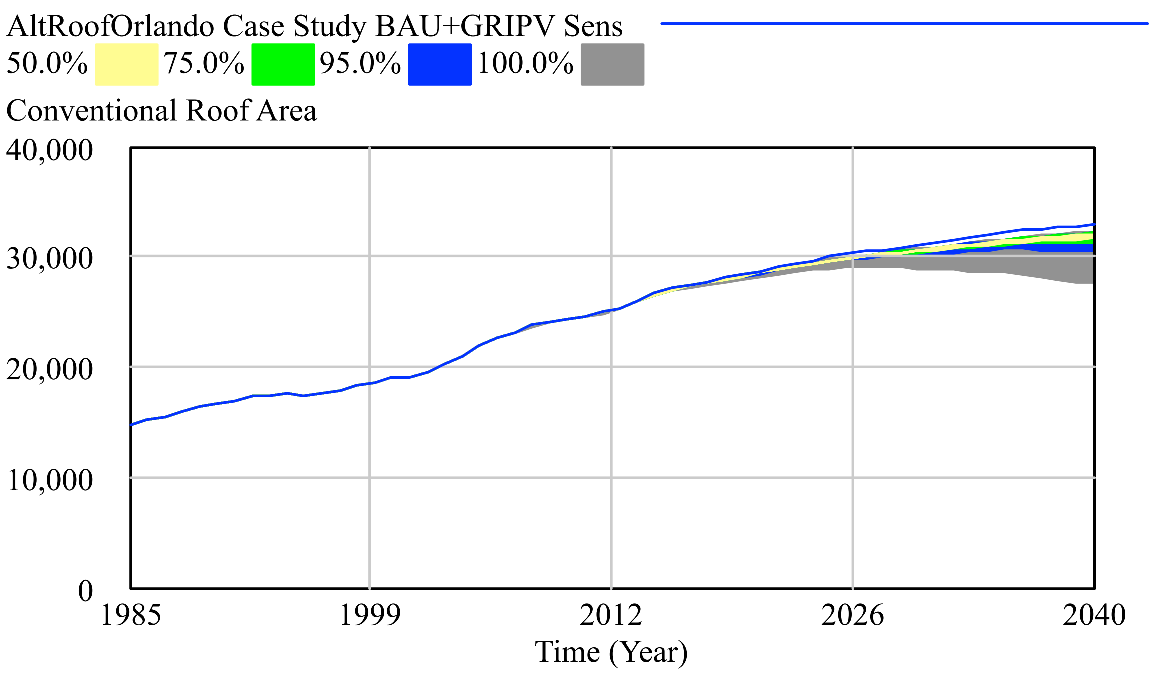


Figure 76: Conventional Roof Area Case Study Uncertainty Graph (GRIPV Included)

6.3.2.2 Green Roof Area

The case study uncertainty results with respect to green roof area are presented graphically in Figures 77 and 78. Both of these graphs indicate much greater potential for green roof adoption (up to 800 acres) with bylaw adoption requirements taken into account, especially in the absence of the GRIPV roofing market, which might otherwise be included in less stringent roofing bylaws. That said, this potential increase in green roof area is also much more variable, with 75% of these 2040 green roof acreage results ranging from about 160 acres to approximately 600 acres (BAU conditions) or from about 100 acres to about 400 acres (BAU+GRIPV conditions), while approximately 95% of these same results were found to reach up to approximately 770 acres (BAU conditions) or up to 560 acres (BAU+GRIPV conditions). These results once again demonstrate that the inclusion of new construction in green roof adoption policies will be a far more effective strategy than focusing solely on conventional adoption strategies (i.e. retrofitting green roofs onto pre-existing buildings). Interestingly, when GRIPV market penetration was included, the uncertainty results demonstrated a significant downward skew compared to when the GRIPV market was not included, but the maximum possible 2040 result (100% confidence range) was not too much smaller than that of the corresponding BAU results at about 720 acres and about 800 acres respectively (Figures 77 & 78 and Figure K19), as opposed to the corresponding regular uncertainty results (Section 6.2.2). This indicates that, with sufficient research and development in green roof design and other relevant external market factors, it is not impossible to develop well-balanced alternative roofing bylaws to encourage market penetration without sacrificing the market growth of any particular option.

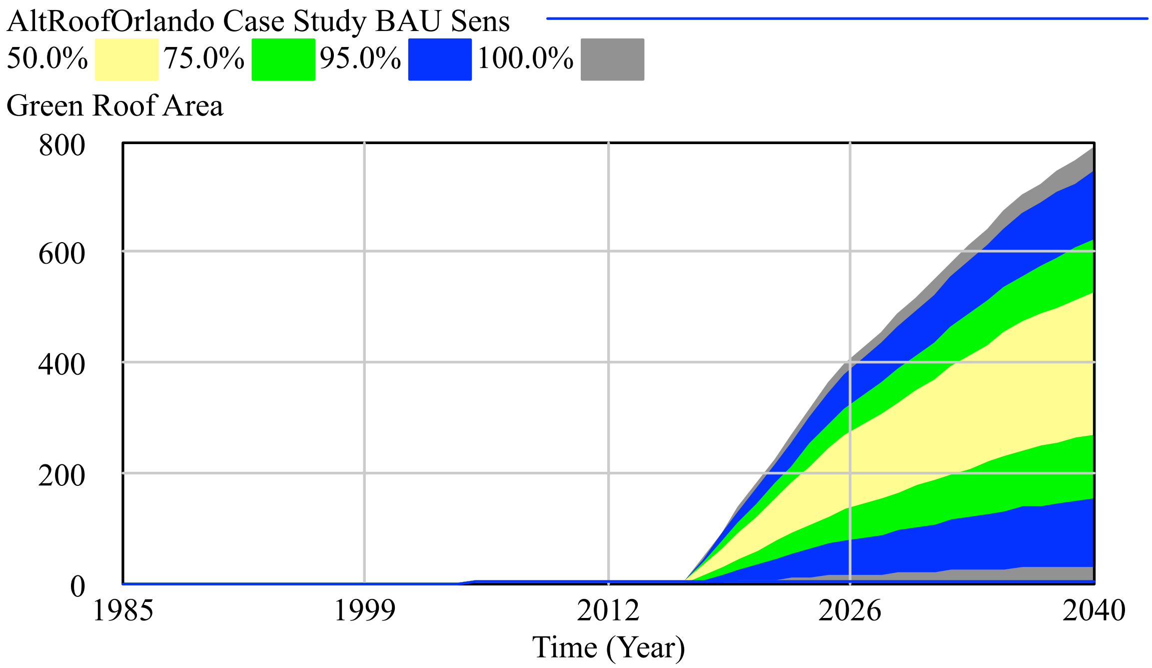


Figure 77: Green Roof Area Case Study Uncertainty Graph (No GRIPV Market)

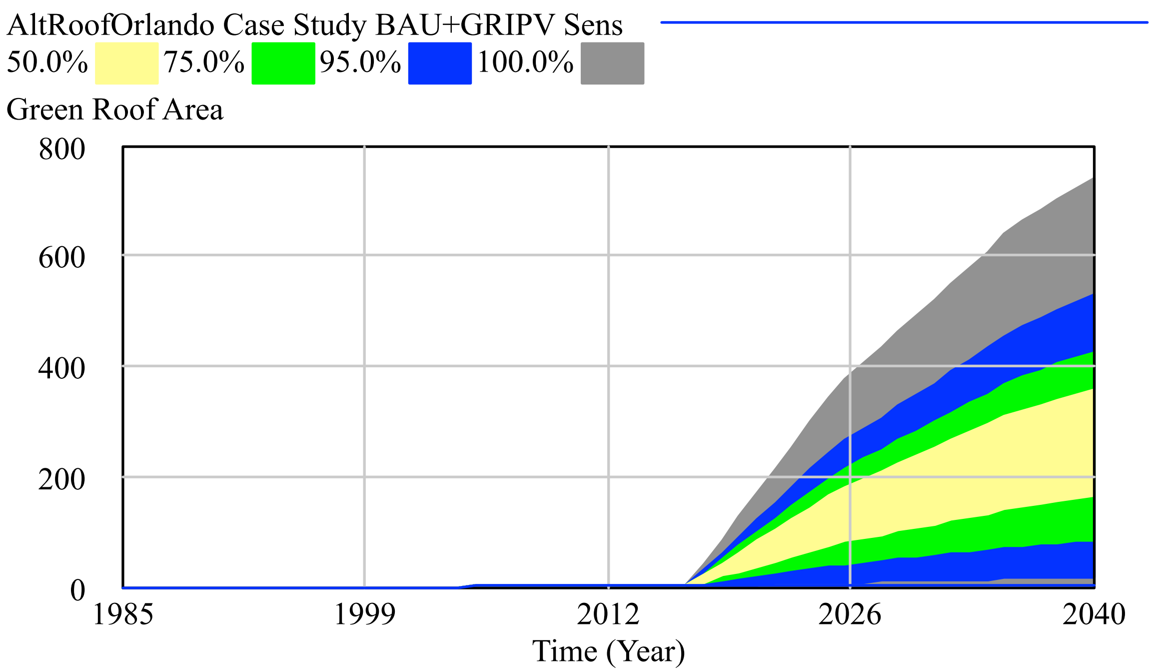


Figure 78: Green Roof Area Case Study Uncertainty Graph (GRIPV Included)

6.3.2.3 Solar Roof Area

The case study uncertainty results with respect to solar PV/BIPV roof area are presented graphically in Figures 79 and 80. The corresponding histograms (Figure K20) indicate a clear improvement over the corresponding regular uncertainty results (Section 6.2.3) with and without the inclusion of the GRIPV market, with a majority of the 2040 solar roof acreage results reaching up to 1,760 acres as opposed to up to 440 acres in the regular uncertainty results. Since the only real changes made between the regular and case study uncertainty results were the inclusion of real-world financial incentives and possible bylaw scenarios, these findings indicate that the solar roof market will tend to respond very well to such policies, especially bylaw adoption policies and/or the encouragement of solar (esp. BIPV) roofing for new construction instead of only focusing on retrofitting pre-existing conventional roofs with solar roofing systems. More generally, these results also once again highlight the increased likelihood of faster solar roof market growth with sufficient emphasis on new construction (esp. in conjunction with future development, particularly as BIPV roofing applications become easier to implement over time), including the potential for solar PV/BIPV roofing to attain significant market shares of up to approximately 5,280 acres (almost 1/6th of the conventional roofing acreage predicted in the BAU scenario).

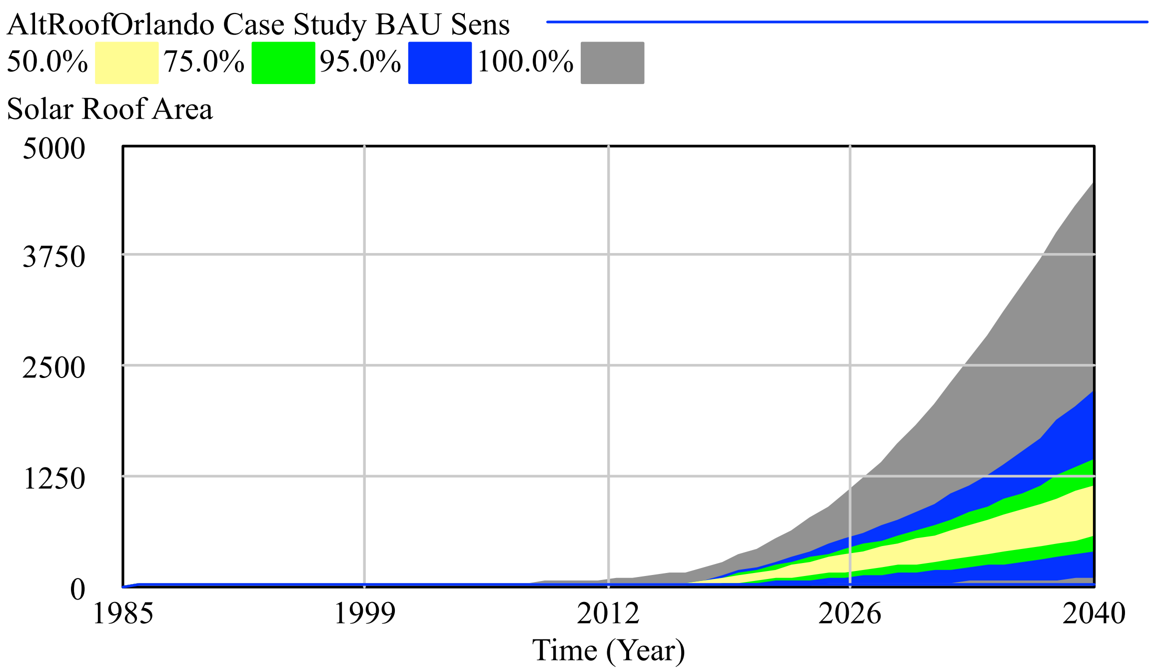


Figure 79: Solar Roof Area Case Study Uncertainty Graph (No GRIPV Market)

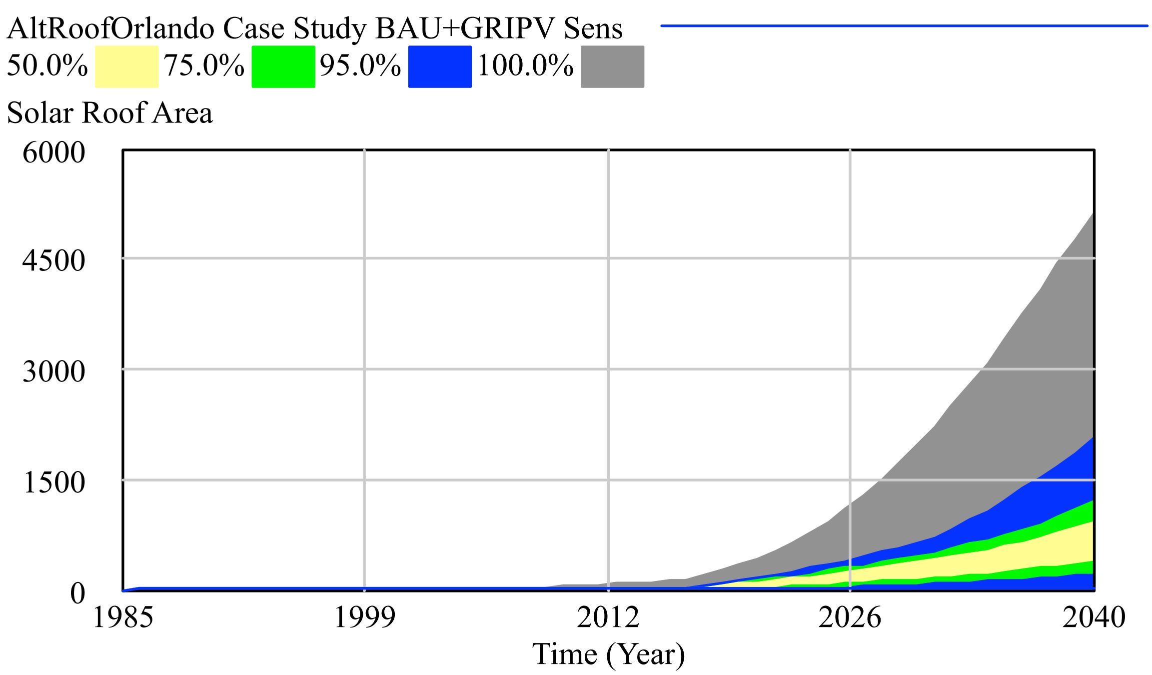


Figure 80: Solar Roof Area Case Study Uncertainty Graph (GRIPV Included)

6.3.2.4 GRIPV Roof Area

The case study uncertainty results with respect to GRIPV roof area are presented graphically in Figure 81. These results tend to follow a trend most similar to the corresponding results for green roofing, but the maximum results for GRIPV roofing were still noticeably less than the corresponding maximum results for green roofing, owing largely to the relative lack of market maturity in the GRIPV roof industry and its subsequent dependence on policy support as previously noted in the regular uncertainty results (Section 6.2.4). A dramatic upward shift in the probability distribution of future GRIPV market trends is also evident in the results in this section compared to the corresponding regular uncertainty results (Section 6.2.3), with a maximum possible result of up to 660 acres in the case study histograms (Figure K21) as opposed to 0.51 acres in the regular uncertainty results. These findings clearly indicate a great deal of potential for the GRIPV roof market to thrive when policy-makers invest in GRIPV systems for new construction, which can be specifically designed to accommodate such roofs, instead of focusing solely on the retrofitting of pre-existing construction.

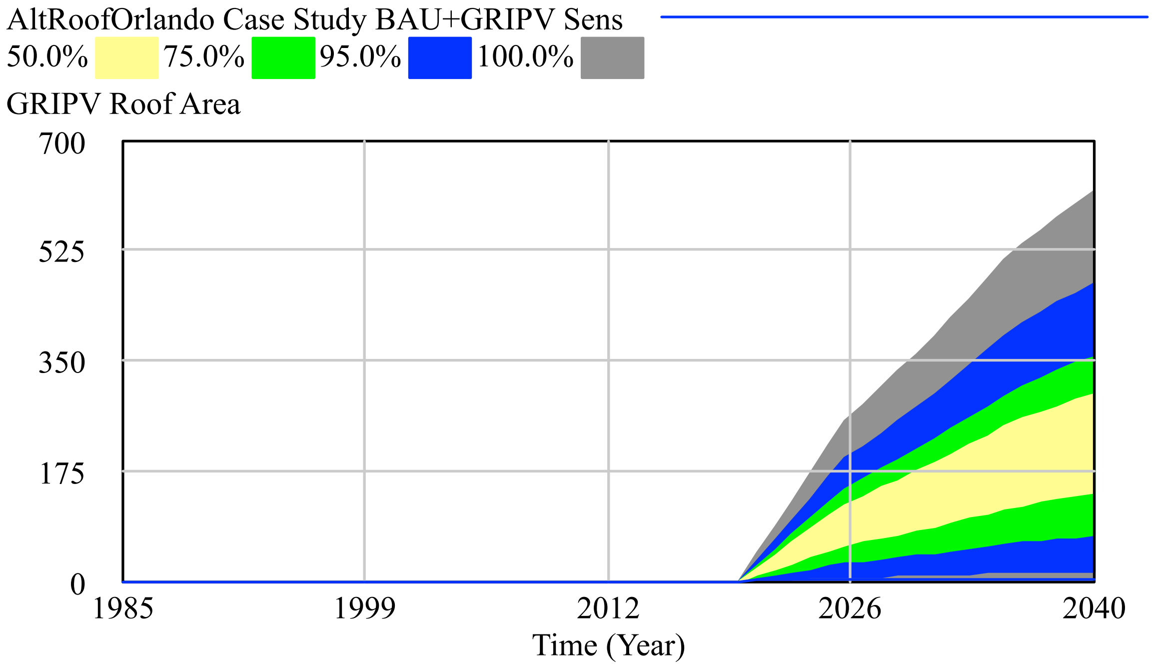


Figure 81: GRIPV Roof Area Case Study Uncertainty Graph

6.3.2.5 Total Annual Runoff Depth

The case study uncertainty results with respect to annual runoff depth will not be presented graphically in this section because the uncertainty ranges are too small in these graphs to make any direct comparison; instead, these graphs will be presented in Figures K16 and K17. However, the corresponding histogram (Figure K22) indicates a much more varied uncertainty distribution showing in urban runoff than what was previously observed in the regular uncertainty results from Section 6.2.5, the latter ranging from 18.67 inches to 18.73 inches, while the case study uncertainty results could reach as low as 18.34 inches with a more conservative majority still potentially reaching as low as 18.45 inches. Although this is still not that much less than the BAU runoff depth (18.71 inches) in terms of overall progress, these results show a clear improvement compared to the regular uncertainty results, indicating that more significant reductions in urban runoff are indeed more likely when the uncertainty variations from this case study are considered, especially when green and/or GRIPV roof adoption is encouraged for new urban construction in addition to pre-existing buildings and/or when new construction moves away from conventional materials (as previously noted in Section 6.3.1.5), although it will also still be essential to include additional policy initiatives to reduce the net demand for new urban construction in order to reduce urban runoff to a greater extent, while the more stringent bylaws previously discussed in Section 6.3.2.1 may also be worth considering if sufficiently feasible. Although these possible initiatives are beyond the scope of this study and, as previously discussed in Section 6.1.1, may not always be realistically feasible (e.g. demolishing occupied houses and/or important infrastructure to return the land to a natural state), other promising solutions may include renovating pre-existing urban buildings/infrastructure and/or demolishing unused or unsafe infrastructure whenever possible instead of clearing undeveloped land for new urban construction, as well as implementing and encouraging socioeconomic programs to reduce the required land space for non-residential buildings (e.g. work-at-home and study-at-home programs to reduce the required land footprints for office buildings and schools, respectively).

6.3.2.6 Air Temperature Anomaly

The case study uncertainty results with respect to air temperature anomaly are presented graphically in Figures 82 and 83. Based on these graphs, the corresponding regular uncertainty graphs (Figures 39 and 40), and the corresponding histograms for all four of the tested uncertainty scenarios (Figure K23), the degree of variability between these uncertainty scenarios is very similar overall, though the upper limit under BAU conditions decreased considerably when case study uncertainty distributions were taken into account. This relative similarity in probability distributions once again indicates that the UHI effect as modeled in this study is heavily dependent on external factors not directly adjusted in any of the policy scenarios considered in this study (esp. with respect to the physical properties and other relevant characteristics of the more predominant conventional and alternative urban surface types) as previously discussed in Section 6.2.6. However, although the probability distributions of the four tested uncertainty scenarios are very similar, the upper limits of the case study uncertainty graphs (esp. those of the 95% and 100% confidence ranges) were found to be visibly lower near the end of the simulation period, if only to a small degree. In other words, the case study factors added to the case study uncertainty analysis (esp. the introduction of alternative roof adoption for new urban construction) do have potential to achieve more significant reductions in the UHI effect, but a reduction in the net demand for new urban construction will likewise be essential in this regard; the latter can be at least partly achieved by implementing the land-efficiency efforts and socioeconomic initiatives previously discussed in Section 6.1.1 and/or by considering the wider bylaw applications discussed in Section 6.3.2.1.

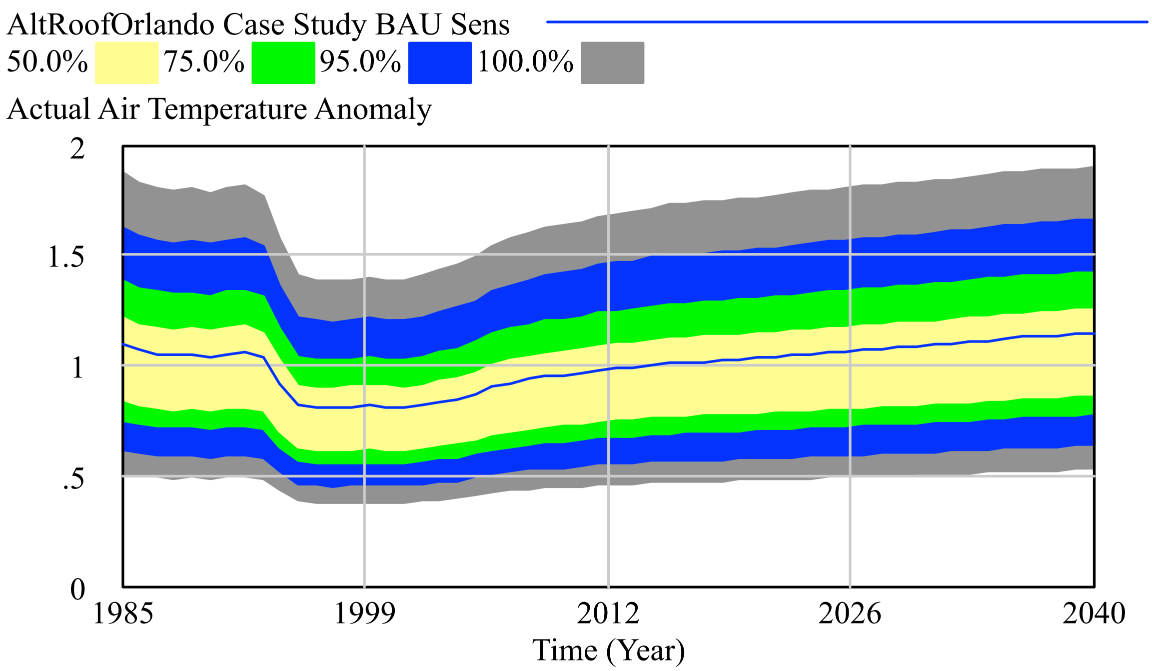


Figure 82: Air Temperature Anomaly Case Study Uncertainty Graph (No GRIPV Market)

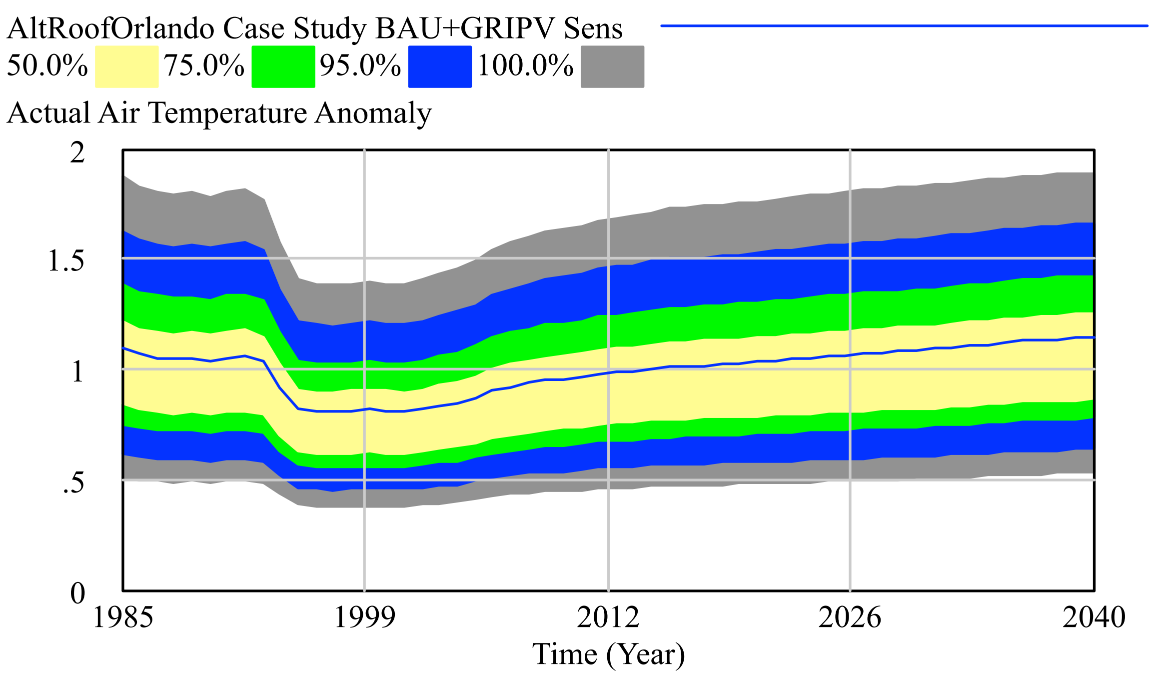


Figure 83: Air Temperature Anomaly Case Study Uncertainty Graph (GRIPV Included)

6.3.2.7 Energy Goal Progress

The case study uncertainty results with respect to energy savings are presented graphically in Figures 84 and 85, with their corresponding histograms presented in Figure K24. These results were much more optimistic than the regular uncertainty results (Section 6.2.7) in that the maximum limits of both graphs were able to exceed the established energy savings goals ("Energy Goal Progress" > 1 (100%)), and there were also significant increases in the upper limits of all other confidence ranges with a majority of results reaching a goal contribution of up to 64% of goal progress, indicating an overall increase in the likelihood of the alternative roofing industry to contribute to energy savings per capita when possible ranges in the case study variables were considered. In particular, based on these results and the corresponding case study policy results (Section 6.3.1.7), greater contributions to energy savings are more likely when alternative roof adoption is encouraged for new urban construction. Unlike with urban runoff and the UHI effect, energy savings in this regard are evaluated on a per-capita basis, so the potential benefits from the land-efficiency efforts and socioeconomic initiatives previously discussed in Section 6.1.1 and/or the wider application of roofing bylaws as discussed in Section 6.3.2.1 are not as clear, but it is still highly possible for the total energy consumption of a particular building (esp. for air conditioning) to decrease in response to reductions in the UHI effect and (more specifically) reductions in the total heat flux through the roof; this possible connection is beyond the scope of this study, but is worth noting nonetheless.

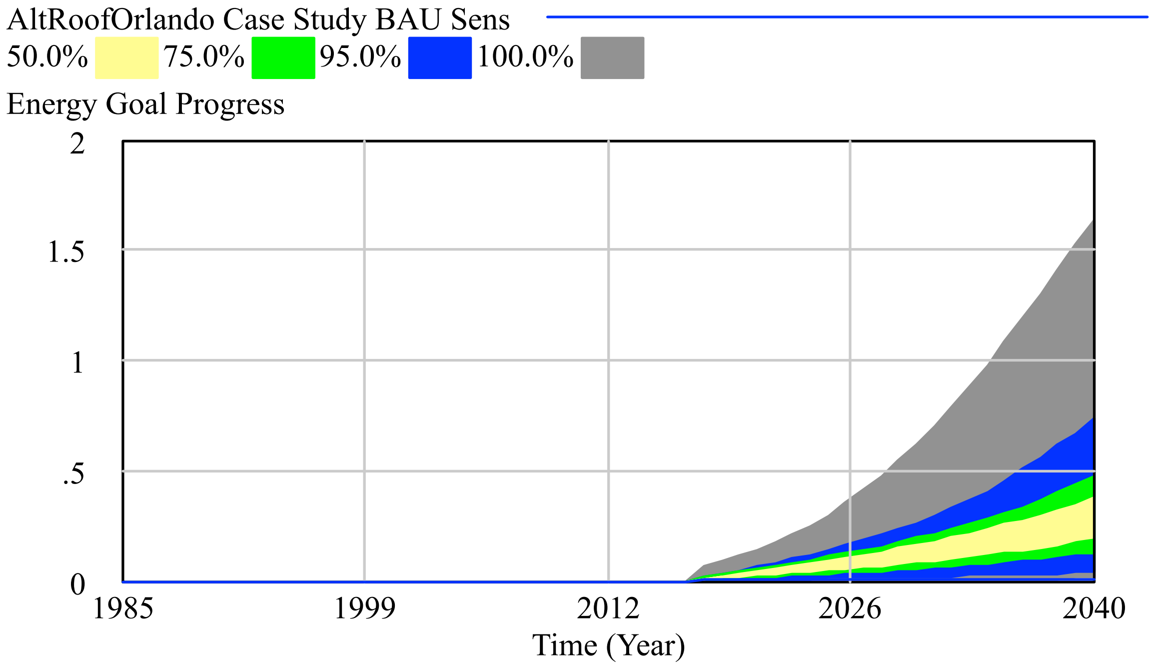


Figure 84: Energy Goal Progress Case Study Uncertainty Graph (No GRIPV Market)

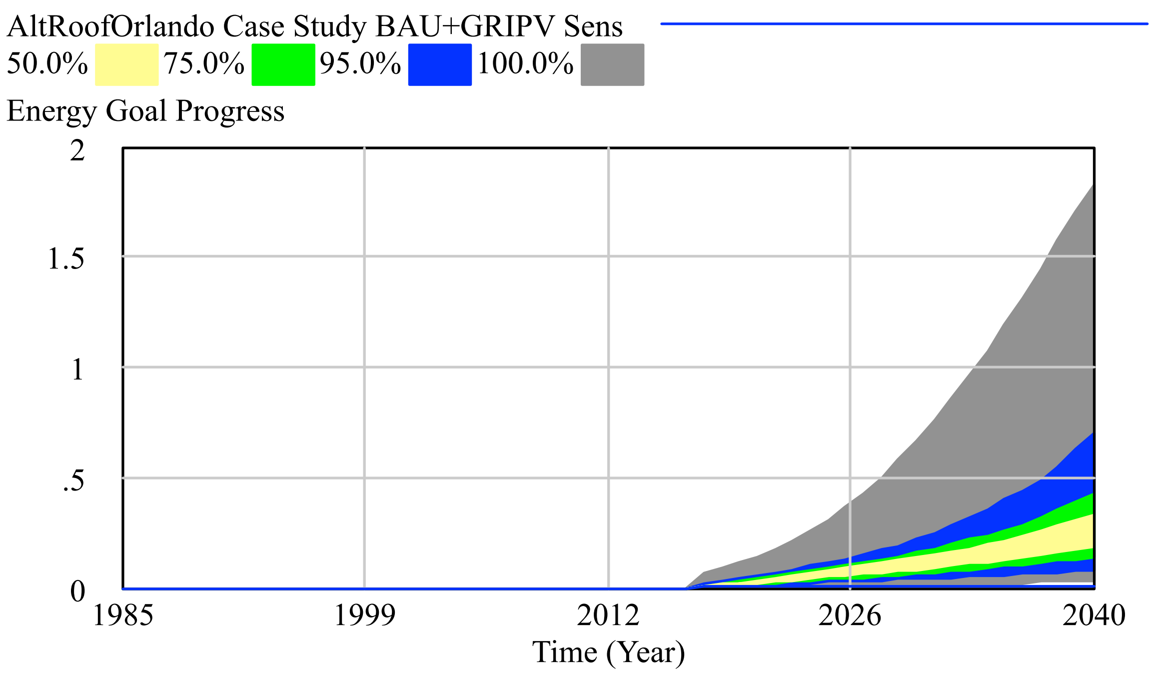


Figure 85: Energy Goal Progress Case Study Uncertainty Graph (GRIPV Included)

6.3.2.8 GHG Goal Progress

The case study uncertainty results with respect to GHG emission reductions are presented graphically in Figures 86 and 87, with their corresponding histograms presented in Figure K25. These results were much more optimistic than the regular uncertainty results (Section 6.2.8) with maximum limits of 14% of goal progress in Figure 86 (BAU conditions) and 16.8% in Figure 87 (BAU+GRIPV conditions), and there were also significant increases in the upper limits of all other confidence ranges with a majority of results reaching a goal contribution of up to 5.6% of goal progress (compared to the regular uncertainty results from Section 6.2.8, where the majority of results reached up to only 1.4% of goal progress), indicating an overall increase in the likelihood of the alternative roofing industry to contribute to GHG emission savings when possible ranges in the case study variables were considered. In particular, based on these results and the corresponding case study policy results (Section 6.3.1.8), greater contributions to energy savings are more likely when alternative roof adoption is encouraged for new urban construction. As with the corresponding results from other analyses included in this study, the case study uncertainty graphs for energy and GHG goal progress both follow very similar patterns in that, in addition to a noticeable change in the upper limit of the 100% confidence ranges of the "GHG Goal Progress" graphs compared to those of the corresponding regular uncertainty results (Section 6.2.8), there were also significant increases in the upper limits of all other confidence ranges, indicating an overall increase in the likelihood of the alternative roofing industry to contribute to reductions in GHG emissions when possible ranges in the case study variables were considered. This similarity in behavioral trends is most likely due to the fact that the two contributors to GHG emission savings are energy savings and carbon sequestration, whereas the latter is a more passive contributor and only applies to green roofs and GRIPV systems. In particular, based on these results and the corresponding case study policy results (Section 6.3.1.8), greater contributions to GHG emission savings are once again more likely when alternative roof adoption is encouraged for new urban construction (i.e. bylaw variable distributions). Unlike with energy savings, however, GHG emission savings as modeled in this study are not evaluated on a per-capita basis, making it possible for the land-efficiency efforts and socioeconomic initiatives previously discussed in Section 6.1.1 and/or the wider bylaw applications discussed in Section 6.3.2.1 to reduce GHG emissions even further than what the results of this analysis may suggest, especially as overall energy consumption (esp. for air conditioning) decreases; this possible connection is beyond the scope of this study, but is worth noting nonetheless.

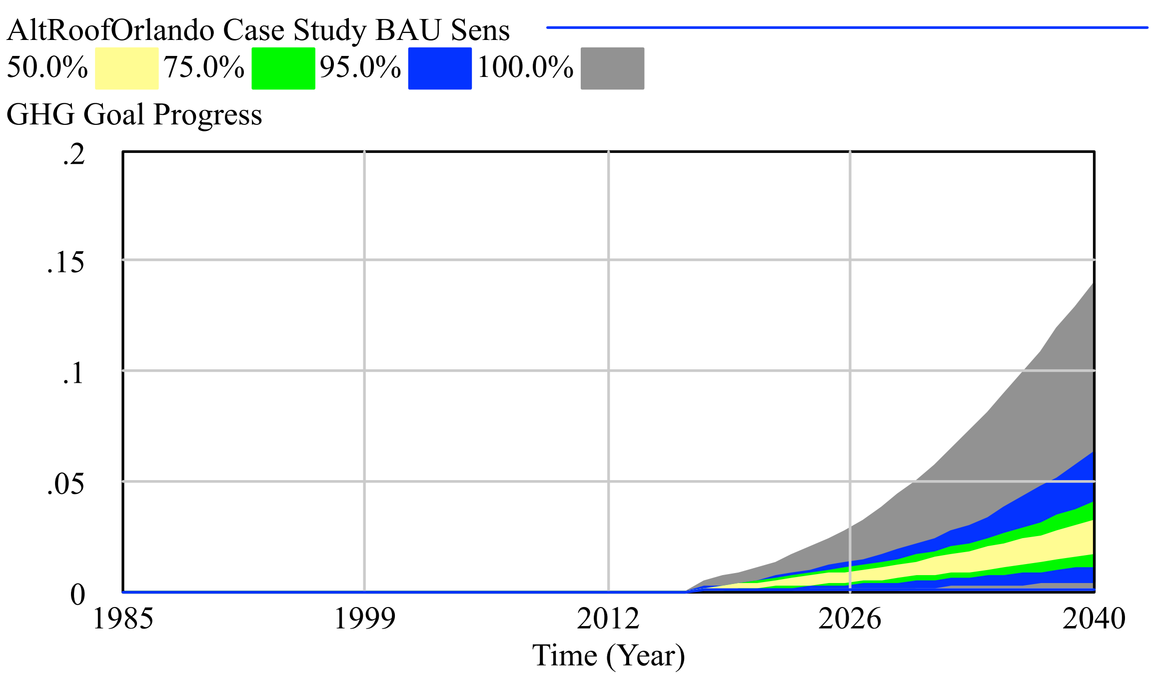


Figure 86: GHG Goal Progress Case Study Uncertainty Graph (No GRIPV Market)

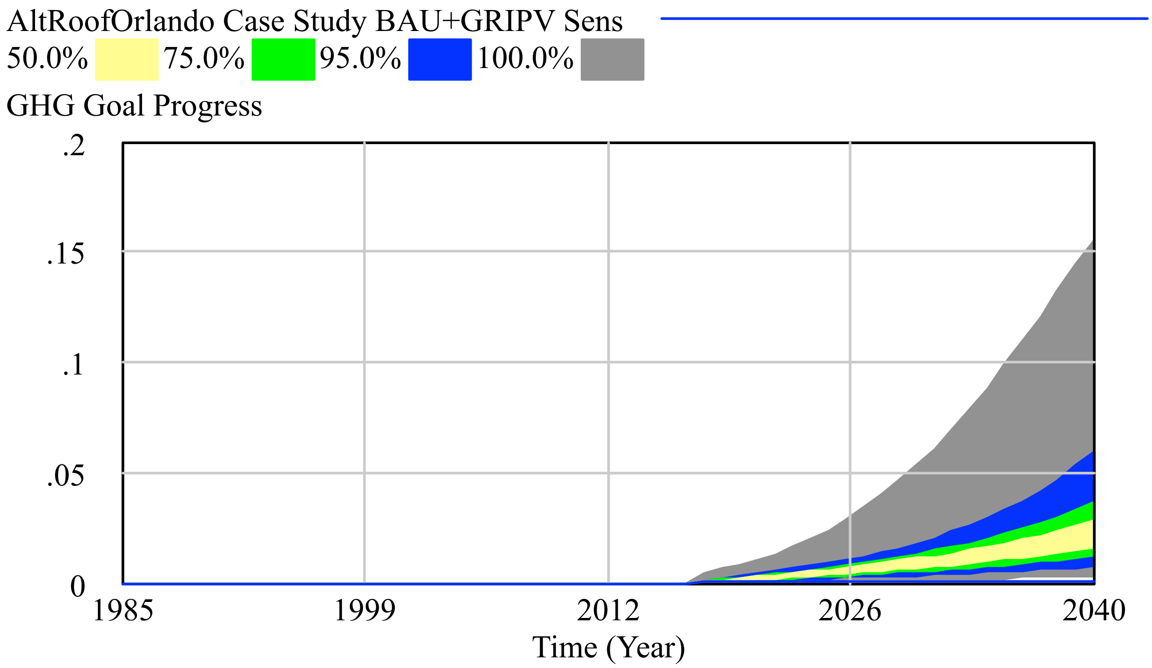


Figure 87: GHG Goal Progress Case Study Uncertainty Graph (GRIPV Included)

6.4 Final Discussion & Conclusions

In this dissertation, a comprehensive System Dynamics analysis of the alternative roofing market in Orlando, Florida was conducted. For this purpose, a "multiple-alternative" SD variation of the Generalized Bass Model (GBM) was developed that essentially consists of three separate GBMs, each modeling the adoption of one of the following three alternative roofing options:

- *Green roofs*,
- *Roof-mounted solar PV systems & building-integrated PV (BIPV) roofing*, and
- *Green Roof Integrated PV (GRIPV) roofing systems*.

Additional sub-models were then added to this SD model to analyze the long-term macro-level impacts of these alternative roofing industries on the following urban environmental impacts and general environmental concerns:

- *Urban runoff*,
- The *Urban Heat Island (UHI) effect*,
- *Energy consumption* (esp. by urban buildings), and
- *Greenhouse gas (GHG) emissions* (esp. by urban buildings).

The finished SD model was then applied to a series of exploratory analyses in order to analyze how different policy and research initiatives can be implemented to optimize the market penetration rates of each of the simulated alternative roofing options for the maximum overall benefit with respect to each of the above-cited environmental concerns. The specific exploratory analyses performed in this dissertation are listed and briefly summarized below:

- First, a *policy analysis* was performed by using the SD model to simulate a number of theoretical policy scenarios representing different levels of societal, economic, and practical investment in the green and solar roofing industries and/or the introduction of GRIPV roofing systems (essentially integrations of green and solar roofing, which have not yet been adopted in the state of Florida) into Orlando's alternative roofing market.
- Second, a *Monte Carlo uncertainty analysis* was performed by running multiple simulations in the SD model based on all possible probability distributions for the external constant variables included in the model, especially those not already included in the above-mentioned policy analysis, and the results were presented in

a series of uncertainty graphs to illustrate the overall range of possible scenarios under business-as-usual conditions (with and without the possible introduction of GRIPV roofing) when all external factors and possible degrees of uncertainty are taken into account.

- Third, an extensive *case study* was performed, consisting of exploratory analyses of the possible implementation of policies already being put into practice in central Florida and/or in other parts of the world, specifically economic incentives per unit of roofing installed and bylaws to require the installation of alternative roofing on non-residential buildings that meet a certain criteria. More specifically, the analyses performed in this case study (with and without the introduction of the GRIPV market) were as follows:
    - A *case study policy analysis* was performed to simulate policy scenarios representing Orlando's implementation of economic incentives and/or installation requirements for one or more types of alternative roofing, based on similar policies already being implemented in central Florida and in other cities in the U.S. and Canada.
    - A *case study uncertainty analysis* was performed by repeating the uncertainty analysis from earlier, this time with the inclusion of appropriate probability distributions corresponding to the real-world policies previously mentioned and all other external factors.

The results of these exploratory analyses have been presented and discussed in Sections 6.1 through 6.3, and there are a number of meaningful conclusions that can be drawn based on these results with respect to Orlando's alternative roofing industry and its impact on the four environmental concerns analyzed in this study. These conclusions have been summarized and discussed in the next seven subsections as they apply to each of the following topics:

- *Section 6.4.1 :: Conventional Roofing*
- *Section 6.4.2 :: Green Roofs*
- *Section 6.4.3 :: Solar PV & BIPV Roofing*
- *Section 6.4.4 :: GRIPV Roofing Systems*
- *Section 6.4.5 :: Urban Runoff*
- *Section 6.4.6 :: The UHI Effect*
- *Section 6.4.7 :: Energy Savings*
- *Section 6.4.8 :: GHG Emission Reductions*

Afterward, a final summary of recommendations based on this research will be provided in Section 6.4.9, after which the limitations of this research will be discussed further in Section 6.5, and finally 6.6 will provide recommendations for future research on the topics analyzed in this study.

6.4.1 Conventional Roofing

Conventional roofs are expected to retain a dominant market share in Orlando's roofing industry regardless of policy intervention, as even the highest possible 2040 market penetration of any given alternative roofing option under any of the tested policies (1,384 acres of solar roofing area in the "SolarBylaw" scenario) is still far smaller than the smallest possible conventional roof acreage in the same year (31,577 acres of conventional roofing area in the

“SolarBylaw” scenario). However, the uncertainty results for conventional roofing (Sections 6.2.1 and 6.3.2.1) and the case study policy results (Section 6.3.1.1) all demonstrated a clear potential to offset and possibly eliminate the current increasing trend in conventional roof market shares with sufficient policy support, advances in alternative roofing technology, and/or improvement in other relevant market conditions, especially with sufficient emphasis on alternative roofing market policies and/or development for new urban construction instead of focusing solely on the retrofitting of pre-existing buildings (the latter of which are almost always originally designed to support conventional roofing and therefore may or may not be realistically able to support a different roofing alternative). These uncertainty results were still unlikely to reach lower than 30,700 acres or 32,680 acres of conventional roofing (with or without the inclusion of alternative roofing bylaws and/or unit-based subsidies, respectively), but could potentially reach as low as 27,480 acres as previously discussed. It was also observed from the corresponding uncertainty results for all three alternative roofing options that the solar PV/BIPV roofing industry was the most likely contributor to these reductions in conventional roof market shares due to the solar roof industry’s market maturity and receptiveness to positive external market influences, although the green and GRIPV roof markets were also shown to be capable of significant levels of market penetration with sufficient policy support (esp. with sufficient emphasis on new urban development as previously discussed) and in fact had the most to gain relative to their respective BAU market projections.

Nevertheless, since even the most optimistic policy and uncertainty results did not reduce conventional roof market penetration any lower than 27,480 acres (which was under the most ideal possible external market conditions), it is clear that additional efforts will also be necessary to more significantly reduce conventional roof market shares and the urban environmental problems discussed in Sections 6.4.5 through 6.4.8. For instance, although urban construction and development in Orlando will inevitably increase to some extent as the population increases and (to a greater extent) as demand for non-residential development (schools, hospitals, office buildings, etc.) also increases, this demand can be reduced or at least offset by finding ways to use pre-existing land development more efficiently and thus reducing the need for new construction in the first place; in the SD model developed in this study, this would correspond to reducing "New Roofing Construction", which is the sole inflow into the "Conventional Roof Area" stock. Not all possible ways to reduce this net demand for new construction may be realistically feasible (e.g. demolishing occupied homes and/or other important buildings and landmarks to return the land to its natural state), but other reduction strategies may be available that can still be highly effective if properly implemented, such as renovating or rebuilding old construction instead of clearing undeveloped land space for new construction, as well as developing and adjusting socioeconomic systems to reduce the required land footprint for certain types of buildings (e.g. opportunities to work and/or study at home and thereby reduce the required land space for office buildings and schools, respectively). Another possible approach may be to lower the minimum building area for the established bylaw criteria (thus requiring alternative roofing on more buildings); this minimum building area is typically smaller in the green roof bylaws observed in the real-world examples in Toronto and Vancouver (Plant Connection, Inc. 2017), but since such roofing bylaws have not yet been implemented in the U.S., it is not yet clear how feasible or how effective the use of alternative roofing bylaws may be in Orlando. Both of these types of policies were beyond the scope of this study, but are worth noting nonetheless.

6.4.2 Green Roofs

Unsurprisingly, if investments in solar roofing are left unchanged, green roof market penetration increases with increasing practical and/or socioeconomic investment in green roofing. However, despite green roof market penetration in all regular policy scenarios being significantly lower than that of solar roofing and marginal compared to conventional roof area (See Appendix I), the green roof market was found to be surprisingly resistant to decreases in market penetration when investments in other roofing alternatives were applied to the model. For example, the 2040 green roof area under the "Solar2+GRIPV" regular policy scenario (no investment in green roofing and maximum investment in other alternative roof types) only decreased by 0.06 acres compared to the 2040 BAU green roof area (1.1 acres versus 1.16 acres). Consequently, although it is clear that Orlando's green roofing industry can benefit greatly from economic, educational, and technological policy initiatives, investments in other alternative roofing options would have a relatively minor impact on green roof adoption, allowing for more diverse investment policies in the alternative roofing market as a whole. However, in any given scenario, green roof market penetration is still significantly lower than solar roof market penetration and is even smaller compared to conventional roof area, while the regular uncertainty analysis results show that the potential variability of external factors is unlikely to have any significant effect on green roof adoption rates. Overall, these results indicate that further industrial/technological development and policy applications will be needed to enhance green roof market penetration to a more significant degree.

On the other hand, Orlando's green roof market also stands to benefit greatly from roofing bylaws and other adoption policies for new urban construction, especially those that focus specifically on the adoption of green roofing, although any such roofing bylaws in which green roofing was an available option also yielded significantly higher market penetration levels than that of the BAU scenario. For instance, the "AllThreeBylaw" scenario had all three of the considered alternative roof types as available options and was therefore the least stringent bylaw scenario for the selection of any particular alternative roof type, but the green roof market penetration under this scenario was still significantly higher than that of the BAU scenario (267 acres versus 1.16 acres), making it reasonably feasible to pursue a more balanced policy approach for multiple environmental concerns as needed. In addition to demonstrating the strong potential of roofing bylaws to enhance market penetration, this finding highlights the importance of encouraging green roof adoption for new urban development and not just for retrofitting onto pre-existing construction, which generally has greater potential for the successful adoption of green roofs and other types of alternative roofing; this is especially true from a practical standpoint, as green roofs work best on buildings specifically designed to accommodate them.

Lastly, regarding the use of subsidies per unit of green roof adoption, it was observed that the offering of such incentives resulted in a minor decrease in green roof market penetration (e.g. 799 acres in 2040 under the "GreenBylaw" scenario versus 775 acres in 2040 under the "GreenEco+GreenBylaw" scenario). This seemingly counterintuitive finding may indicate a reduction in the feasibility of using financial incentives to support the effectively forced adoption of the alternative roofing type(s) specified in the bylaw requirements (as represented by the "Feasibility of Government Support" variable in the model), especially as said bylaw requirements focus more specifically on a particular alternative roofing option and thus require financial support for higher levels of penetration. That said, it must be noted that this decrease is still virtually negligible compared to the overall benefits of roof adoption bylaws relative to the BAU scenario. For instance, despite a decrease in 2040 green roof area of 24 acres between the "GreenBylaw" and "GreenEco+GreenBylaw" scenarios, the 2040 green roof area under the "GreenEco+GreenBylaw" scenario is still approximately far greater than that of the BAU scenario, meaning that the overall market penetration benefits from green roofing bylaws still outweigh any drawback from the cost of offering financial support. Nevertheless, it is still highly recommended for such financial incentives to focus on operational savings (e.g. wastewater cost discounts for green roof owners) where possible, thereby requiring less direct financial support from the government and/or from other private entities and in turn reducing or even eliminating any adverse feasibility impacts.

6.4.3 Solar PV & BIPV Roofing

Unlike the green roof market, which in the regular policy analysis (Section 6.1.2) experienced very little adverse impact from investments in the solar roofing industry, the solar roof market was found to be significantly more sensitive to investments in the green roofing industry, resulting in a decrease in 2040 solar roof area of approximately 13 acres under the "Green2+GRIPV" policy scenario compared to the BAU scenario. However, the solar roof market still maintains the highest penetration levels out of all three alternative roofing options in all of the regular policy scenarios, owing largely to the fact that the U.S. solar energy market as a whole has been continuously advancing and developing over several decades, as opposed to the relatively newer U.S. green roof market and the virtually nonexistent U.S. GRIPV market. Furthermore, just like how green roof market penetration increased significantly with more policy focus in the green roofing industry, the solar roofing market experienced significant growth when policy efforts focused on solar roofing investments, especially when the green roof policy efforts were not included, although there was little difference when the solar roof policy level was changed from Solar1 to Solar2 in any given scenario. It is also worth noting that, in scenarios where investments in both green roofing and solar roofing were included, the resulting decreases in solar roof market penetration were not as drastic as when only green roof investments were applied, with some scenarios having 2040 solar roof areas that were only about 1.1 acres less than that of the BAU scenario. In other words, despite its greater sensitivity to investments in green roofing, the solar roof market still demonstrates enough flexibility to be able to find a reasonable balance for the market penetration levels of all alternative roofing options. It must still be noted, however, that the market penetration of solar roofing in Orlando is still very small compared to the dominant market shares of conventional roofing, even when roofing bylaws are introduced that require solar roofing for new construction, although the latter case demonstrated potential for solar roof area to reach up to 1/6th of the BAU conventional roof area. Nevertheless, these findings indicate that further change and development of the solar roofing market (esp. BIPV development) and of Orlando's construction industry as a whole will be necessary to encourage more effective market penetration in this regard.

The uncertainty results likewise show that solar roof market penetration is highly sensitive to variations in external factors, with final 2040 solar roof areas potentially reaching as high as 4,840 acres with the inclusion of roofing bylaws, although BAU solar roof area is more likely in such circumstances (based on the corresponding histograms) to reach up to 1,760 acres. Regardless, these results clearly demonstrate that it is highly possible for solar PV/BIPV roofing to emerge as a dominant alternative roofing option by the year 2040 with sufficient improvement in PV/BIPV technology and market conditions, which in turn would result in major improvements in the environmental impacts in which solar PV/BIPV market penetration was found to be a viable solution (the UHI effect, energy savings, and GHG emission reductions). Such advancements should therefore be pursued and encouraged whenever they may be feasible, especially since solar roofing's primary competitor in terms of alternative roofing (i.e. green roofs) has previously been shown not to be too sensitive to these same advancements. Since the only real changes made between the regular and case study uncertainty results were the inclusion of real-world financial incentives and possible bylaw scenarios, these findings indicate that the solar roof market will tend to respond very well to such policies, especially bylaw adoption policies and/or the encouragement of solar (esp. BIPV) roofing for new construction instead of only focusing on the retrofitting of pre-existing conventional roofs with solar roofing systems.

6.4.4 GRIPV Roofing Systems

As previously noted, GRIPV roofs have only recently been introduced into the U.S. commercial market, and there is currently zero GRIPV market penetration in Orlando, so it must be noted that the GRIPV market penetration rates illustrated in these results are based on functions of parameters associated with green roofing and solar PV/BIPV roofing individually. Additionally, since the introduction of GRIPV systems into Orlando's alternative roofing market was implemented as a policy in and of itself, only policy scenarios that include the introduction of the GRIPV market will have any results for GRIPV market penetration. That said, the GRIPV policy results (Section 6.1.4) indicate that, despite the 2040 GRIPV market penetration being consistently less than those of green and solar roofing (especially without additional policy investments), the 2040 GRIPV roof area managed to reach 42.4% of the corresponding market penetration of green roofing under the GRIPV-only policy scenario (0.49 acres versus 1.166 acres, respectively). Furthermore, GRIPV market shares were found to benefit greatly from investments into both green roofing and solar roofing with no evident reductions in market penetration (relative to the GRIPV-only scenario) from added investments in either green roofing or solar roofing, which is understandable because GRIPV roof systems are essential a combination of green roofs and solar PV/BIPV arrays. At the highest possible non-bylaw investment level into the alternative roofing industry (the "Green2+Solar2+GRIPV" scenario), GRIPV roof area reaches a 2040 peak value of 7.3 acres (almost 15 times as much as the corresponding BAU+GRIPV acreage in 2040), surpassing the corresponding green roof area in the same scenario to make GRIPV systems the second most popular alternative roofing option after solar roofing. GRIPV roofing also has the most to gain from roofing bylaws that require its adoption for certain types of new construction, with potential growth of over 133,000% relative to the GRIPV-only scenario, making it safe to conclude that emphasis on GRIPV system adoption strategies for new construction in particular will be essential to future growth of the GRIPV roof market in Orlando, as well as in the U.S. as a whole.

It is also worth noting that the results for GRIPV roofing generally tend to follow a trend most similar to the corresponding results for green roofing, meaning that market conditions in the green roofing industry can have a particularly strong influence on the GRIPV market and should be given particular emphasis in future GRIPV development and marketing strategies. For this same reason, GRIPV roof market penetration is also shown not to be particularly sensitive to variations in external factors, with final 2040 GRIPV roof areas likely to reach no higher than 0.51 acres in the regular uncertainty results without any policy implementations and never reaching lower than approximately 0.45 acres. However, despite slightly more limited market penetration in the case study results compared to the corresponding results for green roofing, the GRIPV roofing industry also stands to gain considerably from emphasizing new construction in its market penetration strategies, and its considerable versatility with sufficient market penetration allows it to contribute to environmental improvements (Sections 6.4.5 through 6.4.8) in multiple-alternative bylaw policies that are still comparable to the maximum results in each category, making GRIPV roofing a potentially vital part of a more balanced alternative roofing industry that can more readily address multiple environmental concerns in the future without too much of an adverse impact on effectiveness in any particular category.

In short, these results clearly highlight that the GRIPV roof market has a great deal of potential in Orlando, especially as the green roofing and solar PV/BIPV industries continue to make significant progress in terms of public education, financial support, and technological development. However, despite this potential, GRIPV market shares are still projected to be marginal compared to those of conventional roofing, meaning that extensive future change and development in Orlando's construction industry will still be necessary to encourage more significant macro-level market penetration rates.

6.4.5 Urban Runoff

Despite the undeniable effectiveness of green roofing (including GRIPV roofing) for reducing storm water runoff compared to most other roof types on an individual basis, the overall long-term impact of Orlando's alternative roof market on the average urban runoff depth in the city as a whole was so minimal that no visually significant runoff reductions were evident in any of the policy or regular uncertainty graphs generated in this study, while the case study uncertainty graphs (despite being graphically and numerically more optimistic in this regard) showed very little chance for such reductions in terms of overall progress. From a numerical standpoint, the resulting macro-level runoff reductions never lower the citywide average runoff depth below 18.55 inches (a maximum reduction of only 0.16 inches compared to the BAU scenario) even in more effective green roofing bylaw adoption scenarios, while even the most optimistic uncertainty scenarios (Section 6.3.2.5) expect average citywide runoff depths to be no smaller than 18.34 inches (approximately 0.37 inches lower than that of the BAU scenario). This is due primarily to the fact that the market shares of green roofs and GRIPV roofing, the only two roof types that can reduce urban runoff, range from marginal to nonexistent in Orlando compared to other conventional and alternative roofing materials (despite considerable potential for future market growth as previously noted), to such an extent that their ability to reduce urban runoff in Orlando on a macro-level scale is drastically limited. Based on these findings, although the future development of green/GRIPV roofing and other runoff-reducing infrastructure and materials will inevitably play a crucial role in long-term urban runoff reduction strategies, a more dramatic shift in the construction industry and especially in the socioeconomic systems on which it depends will be essential to achieve any significant change in Orlando's urban runoff flows on a macro-level long-term basis, including (but not limited to) the policy initiatives briefly discussed in Section 6.4.1.

6.4.6 The UHI Effect

The regular UHI effect policy results (Section 6.1.6) yielded no visually significant change in the graphs for air temperature anomaly, but the corresponding case study policy graphs do show a more visible (though still relatively minor) decrease in this anomaly, with the smallest observed result being $+1.125^{0}$F (approximately 0.25% less than the BAU temperature anomaly) under the "GreenBylaw" scenario with and without installation-based financial support even though the optimal regular policy scenario in this regard was the "Solar2+GRIPV" scenario, while all bylaw scenarios in which GRIPV roofing was targeted yielded comparable reductions in this regard of approximately $+1.13^{0}$F or lower. This demonstrates that, although solar roofing is more likely to reduce UHI temperature anomalies under current market conditions due to its relative market maturity, the cooling effects of green and GRIPV roofing are strong enough to make them both more dominant contributors reductions in the UHI effect with sufficient market penetration and development, especially with sufficient policy focus on adoption strategies for new construction, although it was also observed in this regard that even a more lax application of alternative roofing bylaw requirements (e.g. the "AllThreeBylaw" scenario, with and without financial support) was enough to yield more significant reductions in the UHI effect than those observed in any of the regular policy scenarios. These findings once again highlighted the advantages of focusing on new construction rather than the retrofitting of pre-existing buildings when working to address the issue of the UHI effect. On the other hand, the regular and case study uncertainty results demonstrated much more potential variability in this regard, indicating that the UHI effect in Orlando can be reduced even further by targeting each of the external factors accounted for in this study. This primarily includes research and development efforts to optimize the design of the cooling effects and other physical properties (albedo, density, thickness, etc.) of conventional and alternative roofing options as well as other construction materials, as these factors determine the heat absorption rate of a particular surface type and are therefore the main limiting factors for the UHI effect in any urban region. Subsequently, as previously discussed with respect to urban runoff (Section 6.4.5), it will also be critical for builders and policymakers to encourage building designs and socioeconomic reforms that can better accommodate such changes whenever possible so as to avoid the practical and economic pitfalls that currently limit the realistic feasibility of these alternatives. In this regard, the same construction efficiency policies recommended in Section 6.4.1 would also greatly help to more significantly reduce the UHI effect by effectively reducing future urbanization needs, although such policies and their potential effectiveness were beyond the scope of this study.

6.4.7 Energy Savings

It is immediately apparent from the policy results in this study (Sections 6.1.7 and 6.3.1.7) that the solar PV/BIPV roofing market yields the greatest energy savings, partly because solar roofing currently has the most dominant market shares out of all three alternative roofing options, and partly because any type of roofing with solar PV components is able to produce its own energy to offset energy requirements for buildings in addition to using shade to reduce cooling load requirements, as opposed to entirely green roof, which only has indirect cooling load benefits and cannot produce their own electricity. Although the policy results indicated that the maximum potential contribution of the alternative roofing market to energy savings is relatively limited if only "retrofitting" adoption strategies are considered (up to 4.13% of goal progress in the "Solar2+GRIPV" regular policy scenario), this contribution level still indicated a significant increase compared to the corresponding BAU and GRIPV-only contributions (0.64% and 0.70%, respectively), while the corresponding goal contributions with more emphasis on new construction were found to be even more significant (up to 45.16% in the "SolarBylaw" case study policy scenario). Additionally, despite the regular policy results (Section 6.1.7) demonstrating very little change in energy goal progress when GRIPV roofing (the newest alternative roofing option with no market penetration in Orlando as of yet) was introduced into the alternative roofing market, any roofing bylaw scenario from the case study policy results (Section 6.3.1.7) in which GRIPV roofing was available as an option also demonstrated significant increases in progress contributions compared to the BAU scenario (e.g. 6.77% in the "GreenBylaw+GRIPV" scenario), again indicating a great deal of potential for the alternative roofing market (esp. the GRIPV market) to yield significant benefits with sufficient focus on new construction.

Meanwhile, the regular and case study uncertainty results (Sections 6.2.7 & 6.3.2.7) are generally more optimistic. In the regular uncertainty results, the 95% confidence range achieved progress levels of approximately 25% of goal progress with and without the introduction of

GRIPV roofing, while the corresponding total possible ranges (100% confidence) indicate the potential to exceed or at least nearly meet the established 2040 goal. Meanwhile, the case study uncertainty results demonstrated an even greater likelihood to contribute more significantly to energy savings, with 95% upper confidence limits of approximately 70% of goal progress, while the corresponding 100% upper confidence limits far exceeded the established goal at 160% of goal progress under BAU conditions and at 180% of goal progress under BAU+GRIPV conditions. These optimistic uncertainty results indicate that, with a reasonable degree of policy support in conjunction with additional future developments in alternative roofing parameters (e.g. solar PV energy efficiency) and in other external market conditions, it is highly possible for the alternative roofing industry to contribute far more to energy savings in Orlando than what was already observed in the regular and case study policy results as previously discussed. Overall, it can be concluded that the solar and GRIPV roofing industries can provide the greatest contributions to energy savings; more intensive policy efforts (preferably with emphasis on new construction wherever possible) and/or future research and development will still be needed to maximize the energy savings with respect to the 2040 energy demand goals specified for the city of Orlando, but comparable energy savings contributions may still be possible, especially with sufficient emphasis on new urban development (esp. if GRIPV roofing is included as an option in roofing bylaws). Additionally, the construction efficiency policies and wider roofing bylaw implementations previously discussed (Section 6.4.1) may also help to save even more on energy demand, although such policies were beyond the scope of this study.

6.4.8 GHG Emission Reductions

The results for "GHG Goal Progress" consistently followed virtually identical behavioral trends to those previously observed for "Energy Goal Progress", which is not surprising because the primary contributors to GHG emission savings as modeled in this study were the energy savings of each alternative roof type, including reductions in HVAC energy demand and (in the case of solar and GRIPV roofing) the direct production of solar PV electricity to offset or even eliminate the energy demands of a particular building. In the policy results for "GHG Goal Progress" (Sections 6.1.8 & 6.3.1.8), the most significant GHG emission savings were in scenarios in which solar PV/BIPV roofing was the primary focus of policy interventions, indicating that the direct energy production from solar roofs and their higher pre-existing market penetration allow them to contribute far more to GHG savings than any other alternative roofing option. Carbon sequestration by the vegetation of green and GRIPV roofing was also a contributing factor in this regard, but since carbon sequestration is a more passive method of reducing GHG emissions and its effectiveness is heavily dependent on the type of vegetation being planted on the green/GRIPV roof in question, the relatively limited capacities for such vegetation (esp. on extensive green roofs, which are the most commonly installed green roof type) in turn limit the effectiveness of green roof carbon sequestration as a means of reducing GHG emissions. Conversely, the generation of solar PV electricity by solar and GRIPV roof options is less restricted, its only real limitation being the energy efficiency of the solar PV technology being used, which allows solar and GRIPV roofing to offset energy demand (and thus reduce GHG emissions) to a greater degree as solar PV technology improves over time with further research and development. Although green roofing does have the potential for carbon sequestration in addition to its passive cooling benefits, this combination of direct and indirect energy savings from solar and GRIPV roofing systems was enough to make them more dominant contributors to GHG emission savings. That said, overall contributions toward GHG emission reduction goals ("GHG Goal Progress") were also consistently far more limited than those previously observed for energy savings goals ("Energy Goal Progress"), but this is most likely because the energy savings goals modeled in this study were evaluated on a per-capita basis while the corresponding GHG savings goals were measured in terms of the total overall emissions (including those not related to energy consumption) from the city of Orlando, making it impossible to numerically compare the two goal progress percentages.

The BAU and GRIPV-only contributions to GHG savings in 2040 were 0.05% and 0.06% respectively, indicating that the alternative roofing industry as it stands now is unlikely to contribute significantly to large-scale GHG emission reductions on a long-term basis. However, the policy analysis results in this study show that these GHG savings still have the potential to increase significantly, reaching as high as 0.35% in the "Solar2" and "Solar2+GRIPV" scenarios (Section 6.1.8) and 3.82% in the "SolarBylaw" scenario (Section 6.3.1.8). These findings, as previously stated, demonstrate that solar roofing is the preferred alternative roofing option for reducing energy consumption and GHG emissions, but the case study policy results (Section 6.3.1.8) showed that the implementation of roofing bylaw requirements for one or more alternative roof types can still yield significant increases in GHG savings relative to those of the BAU and GRIPV-only scenarios. For instance, the "GreenBylaw+GRIPV" scenario, which implemented roofing bylaws for green and GRIPV roofs only, was able to achieve a 2040 "GHG

Goal Progress" value of 0.62%, which is over 12 times as much as the corresponding BAU GHG savings and over 10 times as much as the GRIPV-only GHG savings.

Despite the relatively small overall contributions to GHG savings goal progress demonstrated in the policy results (Sections 6.1.8 and 6.3.1.8), the regular and case study uncertainty results for "GHG Goal Progress" (Section 6.2.8 and 6.3.2.8) indicated that the inherent uncertainty in Orlando's alternative roofing industry gives it significant potential to contribute even more to GHG emission savings than what was demonstrated in the policy results if the external factors associated with the alternative roofing market can be optimized for this purpose through future research and development. Although the uncertainty results for "GHG Goal Progress" never meet or exceed the established 2040 goal ("GHG Goal Progress" $\geq$ 1 (100%)), the regular uncertainty results (Section 6.2.8) maintained consistent 100% BAU upper confidence limits of approximately 8% to 11.4% without GRIPV roofing and approximately 10% to 11.4% with GRIPV roofing, while the corresponding 100% upper confidence limits for the case study uncertainty results (Section 6.3.2.8) were even higher at approximately 14% without GRIPV roofing and approximately 15% with GRIPV roofing. The inclusion of roofing bylaws and financial support (the case study uncertainty results) was also found to visibly increase the overall likelihood of greater contributions to GHG savings with visible increases in all upper confidence limits compared to the regular uncertainty results, again highlighting the importance of focusing on alternative roofing for new construction in particular. Additionally, the construction efficiency policies and broader bylaw implementations previously discussed (Section 6.4.1) may also help to save even more on GHG emissions by reducing the need for increased urbanization and its associated increases in GHG emissions and/or by further increasing alternative roofing market penetration, although such policies were beyond the scope of this study.

6.4.9 Summary of Recommendations

Not all of the possible recommendations previously discussed were within the scope of this study, but based on the findings of this study as summarized and discussed in Sections 6.4.1 through 6.4.8, the following recommendations can be made with respect to Orlando's alternative roofing industry and its long-term impacts on urban runoff, the UHI effect, energy consumption, and GHG emissions in the city of Orlando as a whole.

- The conventional roofing industry was able to consistently maintain a dominant market share in all simulated scenarios, while the market shares of all three of the alternative roof types considered in this study were marginal in comparison. The regular case study uncertainty results for "Conventional Roof Area" indicated some degree potential to reduce conventional roof market shares to a much more significant extent than what was observed in any of the policy scenarios simulated in this study (esp. in the case study bylaw scenarios), but the results of this study indicate that such a drastic reduction will still require extensive research and development efforts in the alternative roofing industry as well as in the roofing & construction markets in general (esp. if a more moderate and/or diverse investment portfolio is desired), preferably with emphasis on future innovations in new construction and/or urban development strategies whenever possible.

- Looking at the results for scenarios with and without required adoption due to alternative roofing bylaws, such bylaws were found to increase the market penetration rates of any alternative roofing option far beyond what might otherwise be expected of conventional "retrofitting" adoption strategies. Although the legal imposition of literal bylaws may or may not be economically or practically feasible for all building owners, these findings clearly indicate the importance of developing policies and building designs to optimize alternative roof adoption for new construction and thus make alternative roofing options more feasible for future building owners, instead of focusing solely on the retrofitting of pre-existing construction with alternative roofing that may or may not be physically or financially feasible in all cases. For instance, green roofing in today's market is highly susceptible to roof failures in retrofitting applications due to their heavier loads than the conventional roofing that the building in question was originally designed to support; in this regard, the future development and implementation of new building designs that can accommodate these heavier roof loads and/or the development of more lightweight green roofing can go a long way in making green roofs more feasible for future building owners, thus increasing market penetration. Likewise, since the overall performance of solar roofing is heavily dependent on optimizing the placement and angles of its solar PV arrays to maximize their overall electrical output, newly-constructed buildings in future solar PV applications may be specifically designed with building heights and roof slopes to accommodate the optimal placement and angles of such arrays, while newly-emerging forms of BIPV roofing can likewise be used in conjunction with such advances to reduce roof loads and make BIPV roofing more feasible while still optimizing the PV energy output of the roofing in question.

- All three of the alternative roof types considered in this study demonstrated a significant potential for growth (esp. when compared to BAU market penetration rates) when offered sufficient policy support, although a few distinctive behavioral trends were noted for each roof type. Solar roofing consistently had the greatest possible 2040 total area due to the higher maturity level of the solar PV and solar roofing industries compared to those of other alternative roof industries, but the green roof market, despite having less potential for growth, is also more resilient to adverse market conditions and to setbacks from policy investments in other roof types, while the versatility of GRIPV roofing due to its hybrid nature allowed the GRIPV market to benefit from a wider variety of investments (including the highest maximum percent growth rates with bylaw support) and to accommodate more "balanced" investment portfolios with overall environmental improvements that are comparable to their respective maximum results. Consequently, continued investment in and further development of solar roofing will play an essential role in increasing the overall market penetration of alternative roofing in Orlando, but the green and GRIPV roofing industries both have significant potential in this regard as well and should not be overlooked, especially since green and GRIPV roofs can both address the problem of urban runoff, whereas solar roofing is not designed to absorb water and therefore cannot reduce runoff in this manner. Additionally, the overall behavioral trends in "GRIPV Roof Area" (esp. in terms of uncertainty to external factors) were generally found to be more similar to those of "Green Roof Area" than to those of "Solar Roof Area", indicating that the GRIPV market and future GRIPV roofing designs can benefit greatly from future research and development efforts to enhance the practicality and overall market feasibility of its green roof components, including (but not necessarily limited to) reducing their added roof loads and enhancing their symbiotic relationships with the solar roof components of GRIPV systems.

- Urban runoff could not be reduced by more than 0.16 inches in any of the simulated policy scenarios, while the maximum observable reduction from the regular and case study uncertainty results was only about 0.37 inches. This is primarily because the market penetration levels of the only two roofing alternatives that can reduce runoff (green roofs and GRIPV systems), despite significant potential for future growth compared to their BAU market projections, are marginal compared to the combined market shares of the two impervious roof types (conventional and solar roofing). As such, despite the well-documented effectiveness of green and GRIPV roofing to reduce runoff rates on an individual basis, this relative lack of market penetration in the city of Orlando as a whole severely limits the ability of Orlando's green roofing industry and any future prospective GRIPV market to reduce the overall average runoff depth for the entire city on a long-term macro-level basis. The results of this study (esp. the case study results) indicate that future investments, research, and development in green and GRIPV roofing will still play an important role in policy efforts to reduce urban runoff in Orlando (preferably with emphasis on new construction whenever possible), especially as the green roofing industry in Orlando (and in the U.S. in general) continues to grow and mature over time, but these results clearly demonstrate that it will not be enough to rely solely on green/GRIPV roof adoption to reduce Orlando's average annual runoff depth. It will therefore be necessary to continue to develop and discover additional runoff-reducing technologies and initiatives, including (but not limited to) those discussed in Sections 6.5 and 6.6, in conjunction with the green roofs and GRIPV roofing systems analyzed in this study.

- Orlando's UHI effect, represented as the variable "Actual Air Temperature Anomaly", could only be reduced by approximately 0.023^0F in the policy scenarios simulated in this study, although GRIPV roofing systems were found to be the most effective alternative roof type for reducing the air temperature anomaly when sufficient market penetration could be achieved. The maximum reduction in this regard was achieved in the "GreenBylaw" scenario (in which green roof adoption was specifically required for certain types of new construction), but comparable results were still observed in all scenarios in which one or more alternative roofing options (esp. GRIPV roofing) were included as possible options in roofing bylaws, owing primarily to both the strong cooling effects of green roofs (esp. with sufficient market stimulation) and GRIPV roofing's effective combination of the cooling effects of its green and solar components. However, unlike the urban runoff results previously discussed, the corresponding regular and case study uncertainty results indicate a great deal of potential for the UHI effect to be reduced even more significantly if the external factors within the modeled system can be optimized for this purpose. This is especially true for the physical properties of each roof type (albedo, density, thickness, specific heat, etc.) as well as the energy efficiency of solar PV/BIPV/GRIPV arrays and the cooling effects of evapotranspiration from the vegetation of green roofs and GRIPV systems, all of which directly impact the heat absorption rate by different types of roof surfaces and in turn affect the temperature anomaly (esp. in urbanized areas). Some of these factors can be easily adjusted without compromising the performance and/or practicality of a particular roofing option; the albedo of conventional roofing, for instance, can be adjusted with relative ease by using lighter-colored or reflective materials and/or coating, while the albedo of a particular green roof can be enhanced by using lighter-colored plants where available. Other such factors, however, may require further development in the future to improve their overall cooling effect, including further improvements in solar PV/BIPV/GRIPV efficiency to reduce the net amount of heat absorbed by the roof surface and/or the potential discovery of new types of solar PV cells that absorb less waste heat. Still other factors, however, may require additional changes in the construction industry as a whole that were beyond the scope of this study; these additional changes will be discussed in further detail in Sections 6.5 and 6.6, but may include (though are not limited to) the development of new building designs that can accommodate more effective forms of alternative roofing in terms of cooling effects (e.g. semi-intensive and intensive green roofs with higher evapotranspiration rates than the more common extensive green roofs) without sacrificing feasibility.

- The contribution of the alternative roofing industry in Orlando to the city's established per-capita energy savings goals never exceeded 4.13% in any of the regular policy scenarios simulated in this study, but it was still possible for these policy investments in the alternative roofing market to enhance these energy savings to a significantly greater extent than what was observed in the BAU scenario (0.64% contribution to energy savings goals), while the case study policy results (esp. with emphasis on new construction) demonstrated even greater potential in this regard with contributions of up to 45.16% of possible goal progress. Moreover, the regular and case study uncertainty results demonstrated the potential for these energy savings from alternative roofing to increase even further and possibly meet or exceed the established 2040 goal under sufficiently improved external conditions. In short, although it would not be prudent for the city of Orlando to rely solely on the alternative roofing industry to achieve its energy savings goals, it is still highly possible for Orlando's alternative roofing market (esp. the solar PV/BIPV and GRIPV industries) to make more significant contributions toward these goals through a reasonable combination of policy investments and future research and development, especially with sufficient emphasis on new construction as previously discussed and/or in conjunction with other possible recommendations (Sections 6.5 & 6.6).

- Unlike the energy savings goals previously discussed, Orlando's GHG emission reduction goals were measured in terms of overall (rather than per-capita) GHG emissions, making a direct numerical comparison between the two goal progress percentages impossible. Nevertheless, the virtually identical behavioral patterns between these two variables clearly illustrate a strong correlation between energy savings and GHG savings in Orlando's alternative roofing industry, with green/GRIPV roof carbon sequestration as a secondary contributing factor. That said, the contributions of the alternative roofing industry in Orlando to the city's established GHG emission reduction goals was much smaller than the corresponding energy saving contributions (again because the GHG goals were based on overall emissions rather than per-capita emissions) and never exceeded 0.35% in any of the regular or case study policy scenarios simulated in this study, but it was still possible for these "retrofitting" policy investments in the alternative roofing market to enhance these energy savings to a significantly greater extent than what was observed in the BAU scenario (0.05% contribution to energy savings goals), while even greater contributions in this regard were possible in the case study policy results (esp. with sufficient emphasis on new urban development) with contributions of up to 3.82% of overall goal progress. These percent contributions under the simulated policy scenarios are not particularly significant in terms of overall progress, but the regular and case study uncertainty analysis clearly demonstrate the potential of these contributions to increase up to a possible total contribution of approximately 15% based on possible probability distributions in relevant external factors. In short, although it would not be prudent for the city of Orlando to rely solely on the alternative roofing industry to achieve its GHG emission savings goals, it is still highly possible for Orlando's alternative roofing market (esp. the solar PV/BIPV and GRIPV industries) to make more significant contributions toward these goals through a reasonable combination of policy support and future research and development, especially with sufficient emphasis on new construction as previously discussed and/or in conjunction with other possible recommendations (Sections 6.5 & 6.6).

Additional recommendations beyond the scope of this study may be studied in further detail in future research. As such, these additional recommendations will be listed and discussed in greater detail in Sections 6.5 and 6.6.

6.5 Limitations of this Research

This dissertation provided a comprehensive analysis of the green, solar, and GRIPV roofing markets and their potential impacts on urban runoff, the UHI effect, energy consumption, and GHG emissions in the city of Orlando. However, the SD modeling and exploratory analyses performed in this research were not without their limitations, including the following:

- *Urbanization Demand:* In the SD model developed in this study, total annual increase in urban development was represented with a single inflow ("New

Roofing Construction") flowing directly into the "Conventional Roof Area" stock. This inflow was proportional to a number of different factors (net population change, household size, roof area, and non-residential urban construction rates), but the net change in the population was the only such factor whose value changed over time, whereas the other three factors had to be modeled as constants because of insufficient historical data to evaluate their respective behavioral patterns over time. As a result, this study made two assumptions with respect to the overall urbanization of the city of Orlando:

- The total urbanization per capita will remain constant (not accounting for possible socioeconomic changes, new building designs, and/or other market influences that may reduce this urbanization demand), and
- All newly constructed buildings are initially built with conventional roofing that may then be retrofitted with one or more types of alternative roofing via the standard adoption processes modeled in the Generalized Bass Model (not accounting for alternative roof installation on newly constructed buildings).

The case study policy analysis performed in this study (Sections 5.3 and 6.3.1) addressed the latter assumption to a limited extent by using roofing bylaw scenarios to effectively simulate the adoption of alternative roofing for newly constructed non-residential buildings, but these adoption rates had to be simulated using a randomizer due to insufficient available data on the total area of the roofs that met the criteria to require alternative roof adoption, as well as insufficient data on the total area of alternative roofing each year as a result of these bylaws. Additionally, these bylaw adoption rates were also dependent on some factors (e.g. fraction of new roofing for roof areas above a certain amount) that were likewise modeled as constants due to lack of available data, even though such constants can vary significantly for different types of buildings (e.g. schools vs. single-family homes) and may also be subject to changes over time and at different times of day. Consequently, the adoption rates observed in the case study can provide insight to explore the hypothetical impact of alternative roof adoption for new roofing construction, but cannot be considered a completely accurate prediction of the resulting market penetration.

- *Simplification of Surface Properties:* In the developed SD model as a whole, each of the five considered surface types (conventional/green/solar/GRIPV roofing & undeveloped land) have their own set of physical characteristics that the model takes into account, including (but not limited to) the following general characteristics that apply to all surface types:
    - Albedo
    - Density
    - Specific Heat
    - Thickness (for undeveloped land, measured as the soil pedon depth)

  Various other specific properties for each of the five different surface types (e.g. roof lifetimes, solar PV energy efficiency, and evapotranspiration cooling from green/GRIPV roofing and undeveloped land) were also accounted for in this study. However, most of these general and specific parameters were all assigned constant values based on the available literature data, with the sole exception of solar PV energy efficiency, mounting weight, and panel density and thickness, which were allowed to change over time to reflect future improvements in solar PV technology and the gradual introduction of solar BIPV roofing. Despite the comprehensive data from which these constants were derived, and although the uncertainty analyses performed in this study was able to take the inherent uncertainty of these parameters into account, the relatively static nature of most of these parameters due to lack of available data prevented the model from adequately simulating the gradual improvements in all forms of alternative roofing technology (esp. green roofs) and even in conventional roofing designs (e.g. increasing albedo with the introduction of light-colored and/or reflective coating for conventional roofs) as new sustainable roofing methods and modifications continue to be developed and implemented over time. Additionally, regarding green roofs, the green roof characteristic data was based primarily on *extensive* green roofs (the most common green roof type in today's market), which are cheaper and more lightweight than *intensive* or *semi-intensive* green roofs, but also generally tend to not be as directly effective in terms of environmental and/or socioeconomic benefits due to the more limited range of plants and loading capacities that extensive green roofs can support. Consequently, the wide range of possible forms of alternative roofing and other sustainable roofing modifications were not fully taken into account.

- *Limited Application of Economic Incentives:* The economic sub-model in this study covered all three of the key cost-benefit components (costs, operational savings, and financial subsidies/incentives) with respect to each roofing alternative. However, in order to avoid overcomplicating the exploratory analyses conducted in this study, the financial support policies tested in this study were limited to financial subsidies, either reserving fixed portions of the city's GDP to invest in said subsidies (regular policy analysis) or offering subsidies per unit of green roof area and/or solar PV energy generation installed (case study analysis). On the other hand, financial incentives that could instead be applied to reducing costs (e.g. offering a discount off of the initial purchase price per unit of alternative roofing installed) and/or to increasing operational savings (e.g. offering wastewater discounts to building owners who install green or GRIPV roofing) were not included in any of the exploratory analyses performed in this study. Whether or not changing the specific source of financial support in this manner would have any significant impact on the corresponding alternative roofing industries or on the subsequent environmental benefits thereof is unclear, but is worth addressing in future research.
- *Limited Application of Bylaw Implementations:* Since no alternative roofing bylaws have been imposed before in Orlando that would specifically require alternative roofing to be installed on certain types of buildings (making it unclear how feasible or infeasible such bylaws would be for building owners in the current alternative roofing market), a more conservative bylaw implementation

was simulated in the bylaw scenarios of this study, restricting the application of these bylaws to roofs with areas of 100,000 ft^2 or larger whereas the corresponding minimum roof areas in the real world applications of such bylaws are generally smaller (Plant Connection, Inc. 2017). As a result, despite the clearly dramatic improvements in alternative roof market penetration under such bylaws, the true extent of the possible bylaw-related market growth may potentially be much larger than what was shown in this study. Furthermore, other important bylaw-related criteria (e.g. minimum coverage requirements) were ignored to avoid overcomplicating the model.

- *Simplification of SUHI vs. AUHI:* The UHI effect is generally easier to evaluate in terms of surface temperatures rather than ambient air temperatures, primarily because the SUHI effect is a direct function of the physical characteristics of an urbanized surface and the amount of solar radiation to which that surface is exposed, whereas the AUHI effect is also dependent on other meteorological conditions (e.g. wind & rainfall) and other such external factors (e.g. urban development other than roofs) that were all beyond the scope of this research. No clear-cut formula to calculate the ambient air temperature anomaly could be found in any of the available literature, and insufficient data was available to estimate the extent of the SUHI effect in the city of Orlando, so for purposes of this study, the air temperature anomaly was estimated by dividing the calculated surface temperature anomaly by a multiplier ("Surface-to-Air UHI Temperature Ratio") with a value selected via trial and error based on the available air temperature anomaly data and the average SUHI and AUHI temperature anomaly ranges provided in the available literature. However, the meteorological conditions, urban geometry, and other relevant factors associated with a particular urban area can be (and often are) very different from those of other urban areas, making it impossible to estimate the surface-to-air temperature to a more accurate degree given the current lack of available data.

- *Limitations on Validating Energy/GHG Savings:* As previously noted during model validation, the behavioral validity of the energy and GHG sub-models had to be tested through a Behavior Reasonableness Test instead of the generally preferred Behavior Reproduction Test, primarily because there was insufficient historical data on either energy consumption/savings or GHG emissions/savings to produce a reasonable reference mode for either sub-model. The behavior of these sub-models was still found to be reasonably accurate as cited in Section 4.2.2 and in Appendix E, but the Behavior Reproduction Test would have been able to provide additional statistical validation in this regard by numerically measuring the statistical similarity between the model's output and a usable reference mode if enough historical data was available.

These limitations may be partly or completely addressed in future research as discussed in Section 6.6.

6.6 Recommendations for Future Work

Future research on this topic can address the limitations cited in Section 6.5 and extend the current body of available literature in a number of ways. Most notably, the many additional policy initiatives that either had to be excluded to avoid overcomplicating this study or were simply beyond the scope of this research can be modeled and tested in future extensions of this model and in future research. These possible initiatives are listed below, with possible applications explained in detail for each initiative.

- *Reducing/Offsetting Future Urbanization Demand:* The findings of this show consistently demonstrate that conventional roofing is the predominant roof type in the city of Orlando, while the combined and individual market shares for alternative roofing are all marginal in comparison, all while conventional roofing market shares continue to grow as urbanization increases. This predominant trend in the conventional roofing market is due to two crucial factors:
    - *Conventional Building Designs:* Conventional roofing, and conventional building materials in general, have been prevalent in the U.S. construction sector for decades, during which time they have become the norm among materials used in the design and construction of any typical building. On the other hand, the alternative roofing materials and systems analyzed in this study (green, solar, and GRIPV) are relatively new and have not been as widely implemented in the U.S. construction industry, and that coupled with their relative impracticality for buildings originally designed with conventional roofing (e.g. loading and practicality challenges associated

with retrofitting a conventional building with an intensive green roof) makes alternative roofing market penetration more difficult, especially in the U.S. construction sector, which is still very heavily dependent on conventional building designs and materials.

- *Socioeconomic Contributors to Urbanization Demand:* An increase in the demand for urban development within a particular region generally coincides with a need for new urban buildings and infrastructure (homes, schools, hospitals, etc.) to meet the growing needs for the communities within that region. These specific needs and their respective impacts on the demand for urbanization (i.e. how much of which type(s) of buildings/infrastructure must be built) were beyond the scope of this research, but the overall demand for future urban development will generally continue to increase at a steady rate over time if the associated socioeconomic systems and other external factors are left unchanged. Furthermore, since the U.S. construction sector as a whole is heavily dependent on conventional building designs and materials as previously noted, this increasing trend will inevitably result in an increase in the market share of conventional roofing, while the alternative roofing industry has far fewer opportunities for market penetration except for buildings that either have already been designed to support such alternative roofing or can be retrofitted to accommodate a particular alternative roofing option (usually a cheaper and/or more practical variation thereof, though these cheaper alternatives are often less effective than other possible variations, e.g. extensive vs. intensive green roofing).

In this regard, a wide range of policies and initiatives can be potentially effective to address both of these concerns, including policy initiatives beyond those that would be directly applied to Orlando's construction sector. These policies were beyond the scope of this study, but can and should be addressed in future research, including (but not limited to) the following.

- *Urban Efficiency Initiatives:* Urban efficiency initiatives, within the context of the U.S. construction sector, focus on using already developed land and infrastructure as efficiently and sustainably as possible, rather than constantly expanding urbanization into undeveloped land and thus reducing the available land for future development needs. While some theoretical means of achieving this goal would not be realistically feasible (e.g. demolishing occupied homes to return the land to its original undeveloped state), the efficiency of future urban development practices can still be increased by renovating pre-existing buildings/infrastructure for use in new development projects whenever possible and/or demolishing unused or unsafe buildings/infrastructure as needed so that new construction projects can be built in their place instead of having to clear undeveloped land for such projects. In addition to these sustainable construction policies, which can be directly implemented within the construction sector, other socioeconomic policies can also be implemented outside of the construction industry that can also contribute to the overall efficiency of urban development in the future by reducing the need for certain types of buildings. For example, homeschooling programs and online university courses can reduce land footprint requirements for schools, while work-at-home jobs and programs can likewise reduce the required land footprint for office buildings. In this regard, some buildings (e.g. hospitals) cannot always reduce their required land footprints in this manner due to the more vital services that they provide, but may still be able to benefit from future technological advances (e.g. offsite or in-home treatments for minor injuries and ailments) that can facilitate more efficient daily operations within such buildings and reduce the need for such facilities to expand their land footprints in the future. These indirect urban efficiency initiatives can be analyzed in future research with respect to the construction sector as well as the various individual fields and research topics to which they each apply.

- *Development of New Building Designs:* As previously noted, the current prevalence of conventional roofing in urban areas is due in large part to the predominance of standard building designs that do not always efficiently manage their individual land footprints and, moreover, are almost always tailored specifically to conventional roofing materials and thus more difficult to retrofit with alternative roofing afterward. As modern construction technologies and practices continue to advance over time, future academic research and industrial practice can and should work to improve upon the efficiency and sustainability of these standard building designs whenever possible without compromising safety, structural integrity, or economic or practical feasibility. These possible improvements were beyond the scope of this study, but can include (but are not limited to) integrating the pre-existing terrain into the building's design whenever possible so as to minimize the need for drastic changes to the pre-existing landscape, as well as adjusting certain components of the building and its design to better accommodate more land-efficient and generally more sustainable design features (e.g. designing the building's roofing at optimal angles and placements for solar roofing, as well as maximizing the availability of natural sunlight and ventilation through the building as desired to save on energy requirements for lighting and HVAC purposes respectively). In addition to providing greater opportunities for Orlando's construction sector to explore the many possible applications for alternative roofing and thus encouraging its future market penetration, the exploration and development of new construction practices and building design strategies can help to accelerate the U.S. construction sector toward a much more sustainable future, and future research in this regard should not overlook this potential.

- *Broader & More Detailed Policy Applications:* In light of the relatively conservative bylaw implementations simulated in this study, future research on this topic can explore the potential impact(s) of increasing or decreasing the minimum required roof area for a roof area to require the adoption of alternative roofing. Additional bylaw criteria and other policy initiatives and incentives may also be included in this regard, including (but not limited to) minimum coverage requirements and/or bylaw-specific incentives to encourage building owners to install more alternative roofing than the minimum area required under the specified bylaw(s).

- *Additional Sustainable Roofing Upgrades/Methods:* The four developed roof types included in the SD model for this study were as follows:
    - *Conventional Roofs*
    - *Green Roofs* (esp. extensive)
    - *Roof-Mounted Solar PV Systems & Solar BIPV Roofing*
    - *GRIPV Roof Systems*

  However, each roof type in reality has its own separate variations and/or possible upgrades that could potentially be of greater benefit with respect to the environmental impacts considered in the SD model. Examples include the following:
    - Conventional roofs are currently being designed and implemented in today's roofing industry with newer materials designed to absorb less heat and/or reduce heat flux into a building, and can also be coated with a lightly colored and/or reflective paint specifically designed to increase the roof's albedo and thus further reduce its heat absorption rate. These

"upgraded" conventional roofs are collectively referred to as *cool roofs*, though this term also includes all roof types (including green roofs) that are specially designed to reduce the absorption and transfer of heat into and through the roofing material.

- Green roofs, as previously noted in Section 1.1.5, come in extensive, intensive, and semi-intensive varieties. Extensive green roofs were used in the SD model for purposes of this study because they are the most commonly installed type of green roof in today's market, but although extensive green roofs are generally cheaper and more lightweight, their intensive and semi-intensive counterparts can sustain more vegetation as well as a more diverse variety of plant species and ecosystems, making them generally more effective at reducing environmental impacts than extensive green roof systems.
- Currently predominant forms of solar roofing systems generally consist of mono- and/or poly-crystalline silicon solar PV arrays being mounted onto pre-existing conventional roofs, but as previously noted in Section 1.1.6, BIPV systems are currently being designed in today's solar PV industry to more effectively integrate solar PV systems directly into the construction of a particular building. In this study, this was represented as a gradual transition in future years from conventional solar PV panels to BIPV solar shingles, simulated as a gradual change in the physical characteristics (density, thickness, and mounting weight) of the solar panels in question

starting in the year 2019. In addition to this recent introduction of BIPV solar arrays, a wide range of other materials are also being researched and developed for use in solar PV cells (Figure 10); although not all of these other possible materials have yet been developed for commercial use, their future development and eventual introduction to the PV commercial market will be a crucial topic to analyze and discuss in future solar PV research.

    - Lastly, the majority of GRIPV systems currently in use consist of solar PV arrays mounted over green roofs, usually extensive or semi-intensive green roofs. However, since GRIPV systems are essentially a combination of green roofing and solar roofing, any combination of the green roofing and solar roofing varieties previously discussed could potentially be developed in the future, especially since the GRIPV market (esp. in the U.S.) is still in its infancy and has significant opportunities for future growth and technological advancement.

  These variations and upgrades were beyond the scope of this study, but can and should be studied further in future alternative roofing research.

- *Further Exploration of Financial Incentives:* In order to avoid overcomplicating this study, the financial support policies tested in the corresponding exploratory analyses were limited to financial subsidies, but it must not be overlooked that financial incentives can also be applied to reducing costs (e.g. offering a discount off of the initial purchase price per unit of alternative roofing installed) and/or to increasing operational savings (e.g. offering wastewater discounts to building owners who install green or GRIPV roofing). Whether or not changing the specific source of financial support in this manner would have any significant impact on the corresponding alternative roofing industries or on the subsequent environmental benefits thereof is unclear, but is worth addressing in future research, including (but not limited to) the possibility of sensitivity analyses for different types of financial incentives.

Urban development other than roofing (roads, building walls, etc.) and alternative building materials associated therewith (e.g. pervious pavement) can also be included in future research, as well as other forms of green infrastructure that can also help to reduce each of the environmental impacts considered in this study.

Other possible recommendations can include addressing the other limitations cited in Section 6.5, especially once enough data becomes available to allow for more accurate analyses. For example, as more real-world data on the UHI effect in the city of Orlando becomes available (esp. urban and rural surface temperatures), it may be possible to extend the UHI sub-model with a more comprehensive and accurate representation of the UHI effect than the relatively simplistic surface-to-air UHI ratio used in this study. Likewise, the overall effectiveness of alternative roofing bylaws and other alternative roof adoption strategies that target new construction can be modeled more accurately with respect to all relevant external factors (market conditions, necessary criteria for buildings to require alternative roofing, minimum alternative roof area required under roofing bylaws, etc.) as more extensive data on these factors and on the effectiveness of roofing bylaws for alternative roof market penetration becomes available and can be more readily integrated into a future variation of the SD model developed in this study. Lastly, more complete historical data on energy consumption and GHG savings in the city of Orlando would allow future research to further improve the behavioral accuracy and precision of the energy and GHG sub-models, respectively.

APPENDIX A:
LITERATURE REVIEW DATA

Table A1: Annual Green Roof Rainfall Retention (AGRRR) Efficiencies From Literature

Study	*(GSA 2011)*	*(Garrison et al. 2012)*	*(Li and Yeung 2014)*	*(Berghage et al. 2009)*
Location	U.S.A.	Southern California	*Not Specified*	U.S.A.
Annual Green Roof Rainfall Retention (AGRRR)[1]	AGRRR ≥ 65%	35% ≥ AGRRR ≥ 50% *(Pre-Estimated)*	40% ≥ AGRRR ≥ 60%	AGRRR = 50%

[1]Evapotranspiration (ET) is assumed to be included unless otherwise stated.

Study	*(Palla et al. 2010)*	*(Hathaway et al. 2008)*	*(Wanielista et al. 2008)*	*(VanWoert et al. 2005)*
Location	Italy	North Carolina	Florida	Michigan
Annual Green Roof Rainfall Retention (AGRRR)[1]	40% ≥ AGRRR ≥ 80% *(AGRRR = 65% on average in the U.S.)*	AGRRR = 64%	33% ≥ AGRRR ≥ 51% *(w/o cistern)*	AGRRR = 50.4% *(w/o vegetation)* AGRRR = 60.6% *(w/ vegetation)*

[1]Evapotranspiration (ET) is assumed to be included unless otherwise stated.

Table A2: Albedo & Cooling Fractions From Literature

Study	*(GSA 2011)*	*(Garrison et al. 2012)*	*(Li and Yeung 2014)*	*(Lazzarin et al. 2005)*	*(Gaffin et al. 2010)*
Location	U.S.A.	Southern California	*Not Specified*	Italy	New York
Albedo Value(s)	0.25-0.3 (Vegetation & Green Roofs) 0.1-0.35 (Conventional Roofing Tiles)	0.25-0.3 (Green Roofs) 0.08-0.18 (Conventional Roofs)	0.22-0.85 (Green Roofs w/ Vegetation) 0.066 (Conventional Roofs)	0.23 (Green Roofs) 0.1 (Conventional Roofs)	0.2 (Green Roofs) 0.05 (Conv. Roofs)
Cooling Value(s) as a Fraction of Insolation	*Not Applicable*	*Not Applicable*	*Not Applicable*	0.12-0.63 (Green Roof ET[1])	*Not Applicable*

[1]ET = Evapotranspiration

Study	*(Dominguez et al. 2011)*	*(Protogeropoulos and Zacharious 2010)*
Location	California	Greece
Albedo Value(s)	0.178 (Solar PV Panels)	0.15 (Solar PV Modules)
Cooling Value(s) as a Fraction of Insolation	*Not Applicable*	*Not Applicable*

Table A3: Heat Flux Rates From Literature

Study	*(Gaffin et al. 2010)*	*(Sonne 2006)*	*(Wang et al. 2006)*	*(Dominguez et al. 2011)*
Location	New York	Florida	China	California
Average Cooling Load	-0.07 W/m^2 (Green Roofs w/ shade) +0.27 W/m^2 (Green Roofs w/o shade) +1.79 W/m^2 to +2.11 W/m^2 (Conventional Roofs)	+1.23 W/m^2 (Green Roofs) +1.51 W/m^2 (Conventional Roofs)	+3.224 W/m^2 (BIPV Reduction versus Conventional Roofs on Average)	+3.17 W/m^2 (BIPV Reduction versus Conventional Roofs)
Average Heating Load	-4.03 W/m^2 (Green Roofs w/ shade) -3.05 W/m^2 (Green Roofs w/o shade) -3.85 W/m^2 to -4.45 W/m^2 (Conventional Roofs)	*Not Applicable*	+2.864 W/m^2 (BIPV Reduction versus Conventional Roofs on Average)	-0.43 W/m^2 (BIPV Reduction versus Conventional Roofs)

Table A4: Green Roof Carbon Sequestration Rates From Literature

Study	*(Getter et al. 2009)*	*(GSA 2011)*
Location	Michigan	U.S.A.
Green Roof Carbon Sequestration Potential	5.6 metric tons CO_2/acre ±1.1 metric tons CO_2/acre	0.048 metric tons CO_2/acre *(w/o reflectivity)* 31.944 metric tons CO_2/acre *(w/ reflectivity)*

Table A5: Roof Lifetimes From Literature

Study	*(Breuning 2016c)*	*(GSA 2011)*	*(Garrison et al. 2012)*	*(AMS 2016)*	*(NREL 2016b)*
Location	Maryland	U.S.A.	Southern California	Not Specified	U.S.A.
Green Roof Lifetime	40 years	25 years – 60 years *(Based on 6 studies)* *(Average = 42.3 years)*	20+ years longer than conventional roofs	*Not Applicable*	*Not Applicable*
Conventional Roof Lifetime	*Not Applicable*	14 years – 30 years *(Based on 7 studies)* *(Average = 18.86 years)*	*Not Applicable*	8 years – 15 years	*Not Applicable*
Solar PV Module Lifetime	*Not Applicable*	*Not Applicable*	*Not Applicable*	*Not Applicable*	25 years – 40 years

Table A6: Green Roof Costs From Literature

Study	*(Breuning 2016c)*	*(GSA 2011)*	*(Garrison et al. 2012)*	*(EPA 2008)*
Location	Maryland	U.S.A.	Southern California	U.S.A.
Green Roof Installed Cost	$14.00/ft^2 *(w/o load-related costs)* $18.00/ft^2 *(w/ load-related costs)*	$24.50/ft^2 *(National Average)* $23.95/ft^2 *(Washington, D.C.)*	$10.00/ft^2 to $25.00/ft^2	$5.00/ft^2 to $25.00/ft^2 *(Extensive Green Roofs)*
Green Roof O&M[1] Cost[2]	$0.38/ft^2-year	$0.27/ft^2-year *(National)* $0.36/ft^2-year *(Washington, D.C.)*	$0.20/ft^2-year to $1.25/ft^2-year	$0.75/ft^2-year to $1.50/ft^2-year

[1]O&M = Operation & Maintenance
[2]Excluding operational savings and financial incentives

Table A7: Roof Loads From Literature

Study	*(Lazzarin et al. 2005)*	*(Wang et al. 2006)*
Location	Italy	China
Conventional Roof Load	33.58 kg/ft^2	33.71 kg/ft^2

Study	*(GSA 2011)*	*(EPA 2008)*	*(Capozzoli et al. 2013)*
Location	U.S.A.	U.S.A.	Italy
Green Roof Load	20.06 lb/ft^2 – 42.23 lb/ft^2 *(Maximum ("Wet") Dead Load)*	13 lb/ft^2 – 50 lb/ft^2 *(Extensive Green Roofs)*	35.65 lb/ft^2 *(Extensive Green Roof) (Excluding Standard Roofing Layers)*

Study	*(Wang et al. 2006)*	*(United Solar Ovonic 2004)*
Location	China	Not Specified
Solar PV Array Load	1.66 kg/ft^2 *(Standard PV Module)*	0.3 kg/ft^2 *(BIPV Solar Shingle)*

Table A8: GRIPV Roof System Parameters From Literature

Study	*(Köhler et al. 2007)*	*(Chemisana and Lamnatou 2014)*	*(Witmer 2010)*	*(Ogaili 2015)*	*(Hui and Chan 2011)*
Location	Germany	Spain	U.S.A.	Oregon	Hong Kong
GRIPV Energy Efficiency Improvement	+1% to +10% *(Average = +6%)*	+1.29% *(w/ Gazania Rigens)* +3.33% *(w/ Sedum Clavatum)*	+0.55% *(Vs. Black Roof PV)* +0.077% *(Vs. White Roof PV)*	+1.0% to +1.2% *(Vs. Black Roof PV)* +0.7% to +0.8% *(Vs. White Roof PV)*	+4.3% *(Field Measurements)* +8.3% *(EnergyPlus Simulation)*
GRIPV Green Roof Vegetation Growth	+5.6% of added plant cover *(1999-2006)*	*N/A*	*N/A*	*N/A*	*N/A*

APPENDIX B:
SELECTED & EXCLUDED SYSTEM VARIABLES

Table B1: Land Area & Expansion Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Net Land Expansion Rate	• Net Land Expansion • Total Land Area • Conventional Roof Area • Green Roof Area • Solar Roof Area • GRIPV Roof Area • Undeveloped Land Area	*N/A*

Table B2: Population & New Construction Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Non-Residential Construction • Net Population Change Rate	• Population • Net Population Change • New Roofing Construction	• Non-Roof Development

Table B3: Main Diffusion Model Variables for Each Alternative[1]

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Advertising & Public Education • Contact Rate • Purchase Fraction	• Alternative Roof Adoption • Alternative Roof Area • General AltRoof Demand • Relative Attractiveness of Alternative • Word-of-Mouth Effect	• Developed Land Area Other Than Roofs

[1]These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.

Table B4: Urban Runoff Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Annual Rainfall • Pervious ASRC[1]	• Average Overall ASRC • Base Runoff • Runoff Concerns • Total Runoff	• Depression Storage • Evapotranspiration from Undeveloped Land • Irregularities in Impervious Surfaces

Table B5: Urban Heat Island Effect Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Annual Insolation • Rural Air Temperature	• Air Temperature Anomaly • Average Cooling Effect • Average Resistance to Increases in Surface Temperature • Average Surface Temperature Change • Base Surface Temperature Change • Surface Temperature Anomaly • UHI Concerns	• Moisture Content • Saturation Capacity

Table B6: Energy Savings Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Per Capita Energy Savings Goal • PV Energy Research	• Cooling Energy Savings • Energy Savings Per Capita • Energy Goal Progress • PV Energy Development • PV Energy Efficiency • Total Energy Savings	• Energy Demand Savings From Any Other Methods or Technologies

Table B7: GHG Emission Savings Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• GHG Emission Savings Goal • Power Grid GHG Emission Factor	• Carbon Sequestration • GHG Goal Progress • Total GHG Emission Savings	• Carbon Sequestration from Undeveloped Land • GHG Emission Reduction Rates From Any Other Methods or Technologies

Table B8: Financial Incentive Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Net GDP Change Rate • Green GDP Investment • Private Green Subsidies • Private Solar Subsidies • Solar GDP Investment	• Feasibility of Government Support • GDP • Net GDP Change • Standardized Green Incentives • Standardized GRIPV Incentives • Standardized Solar Incentives	• Subsidies for Conventional Roofing

Table B9: Cost Effectiveness Variables for Each Alternative[1]

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	*N/A*	• Alternative Cost Effectiveness • Alternative Electric Utility Savings • Alternative Operational Savings • Alternative Wastewater Savings • Alternative Gross Investment Cost • Alternative Financial Incentives • Standardized Alternative Incentives • Alternative SNV[2] • Conventional SNV[2] • Other AltRoof SNVs[2]	• Carbon Tax Savings from GHG Emission Reductions • Possible Savings From Different Conventional Roof Types

[1]These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.
[2]Standardized Net Value

Table B10: Practicality Variables for Each Alternative[1]

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Alternative Roof Additional Loads • Alternative Roof Density • Alternative Roof Lifetime • Alternative Roof Thickness • Alternative Contractor Training • Conventional Roof Lifetime • Other AltRoof Lifetimes	• Alternative Contractor Experience • Alternative Contractor Learning • Alternative Practicality • Alternative Roof Load • Conventional Roof Load • Other AltRoof Loads • Market Impact of Alternative Lifetime • Market Impact of Alternative Loading	• Additional Insulation Not Common to All Roof Types • Practical Applications Other Than Roofing • External Upgrades Not Typically Included With a Particular Surface Type

[1]These variables all apply to green, solar, and GRIPV roofing options, although their respective quantitative values will vary as shown in Appendix D.

APPENDIX C:
RELEVANT REAL WORLD ALTERNATIVE ROOF DATA

To ensure that the model developed in this study represents the city of Orlando and/or the alternative roofing options being modeled as realistically and as accurately as possible, parameter values will be directly derived from real world alternative roofing examples with emphasis on real world data from the city of Orlando whenever possible. These real world examples and the data to be applied to this model are all summarized in the tables in this section.

First, the soil/media depths of three green roofs in Orlando are summarized in Table C1, and will be used in conjunction with the available literature data to estimate averages and probability distributions for green roof thickness, density, and specific heat. These three green roofs are listed below with their corresponding references:

- University of Central Florida (UCF) Student Union (Greenroofs.com 2017a; Wanielista et al. 2011)
- New American Home 2007 (Greenroofs.com 2017b; Kelly et al. 2007)
- University of Central Florida (UCF) Stormwater Management Academy Laboratory (Greenroofs.com 2017c; Wanielista et al. 2011; Kelly et al. 2007)

Table C1: Real World Green Roof Total Soil & Media Depths

Green Roof	*UCF Student Union*	*New American Home 2007*	*UCF Stormwater Management Academy Lab*
Total Soil & Media Depth	8 inches	7.5 inches	4 inches

Regarding rainfall retention, the New American Home was the only real green roof for which a runoff retention fraction was available *(95% retention)* (Greenroofs.com 2017b); this data point will likewise be included in conjunction with the relevant literature data to estimate the average value and probability distribution of annual green roof rainfall retention as modeled in this study.

Next, the solar PV capacities per unit of module area have been found with respect to two large-scale solar PV roofs in Orlando, and are summarized in Table C2. The only literature data available in this regard was for utility-scale solar PV arrays, which are not applicable for purposes of this study, so the values in Table C2 will be used as the primary basis to estimate the average and the probability distribution of PV power capacity per acre as modeled in this study. The two solar roofs examined for this purpose are listed below with their corresponding references:

- Orange County Convention Center (OCCC) (OCCC 2017a,b,c; Runyon 2012; Runyon 2016)
- Darden Restaurants Support Center (Bonczek 2012; Spear 2012)

Table C2: Real World Solar Roof Power Capacities Per Unit Area

Solar PV Roof	*Orange County Convention Center*	*Darden Restaurants Support Center*
Solar PV Power Capacity Per Unit Area	534.29 kW/Acre	692.25 kW/Acre

Finally, regarding GRIPV roofing, the only commercially available GRIPV system in the U.S. is the Sun-Root™ Solar Garden system. Although no such system has ever been installed in Orlando as of now, one Sun-Root™ system has been installed on NYC Parks' 5-Borough Administration Building in 2012 on Randall's Island in New York City. The relevant data directly derived from NYC Parks' description of this system (NYCPR 2013) will be used in conjunction with the available data from the Sun-Root™ system manufacturers (Optigreen International AG 2017a,b) and the available literature data to estimate the averages and probability distributions for the thickness, density, and specific heat of the green roof component of the GRIPV system, assuming that all relevant specifications for the solar roof component will remain the same as that of a standard solar PV/BIPV roof. The relevant data from the NYC Parks system is summarized in Table C3, and the finalized range of possible "designs" for the GRIPV green roof component based on these parameters, the manufacturers' design specifications, and any necessary input from the literature will be summarized in Table C4.

Table C3: NYC Parks GRIPV Roof Data (NYCPR 2013)

Parameter	*Value*
Green Roof Component Weight	14 lb/ft^2 *(Dry)* 21 lb/ft^2 *(Wet)*
Total Installation Cost	\$16.00/ft^2

Table C4: Estimated GRIPV Green Component Model Design Ranges

GRIPV Green Component Parameter	*Minimum Value*	*Average Value*	*Maximum Value*
Density	37.26 kg/ft^3	41.14 kg/ft^3	42.92 kg/ft^3
Thickness	1.17 ft	1.33 ft	1.50 ft
Specific Heat	$4.44\times10^{-4}\,\frac{kWh}{kg*degF}$	$4.62\times10^{-4}\,\frac{kWh}{kg*degF}$	$5.03\times10^{-4}\,\frac{kWh}{kg*degF}$

The Sun-Root™ system is also said to be able to increase solar PV efficiency by 5% compared to a standard roof-mounted solar PV array (GRT 2017; Optigreen International AG

2017c); this data point will likewise be included in conjunction with the relevant literature data to estimate the average value and probability distribution of the percent improvement in GRIPV efficiency compared to standard PV efficiency.

APPENDIX D:
DETAILED MODEL FORMULATION & REFERENCE MODES

Table D1: Time-Series Parameter Data Sources

Model Parameter(s)	*Annual Rainfall*	*Average Annual Rural Temperature*	*GDP & Change Rate*
Lookup Data Source(s)	(FSU 2016)	(FSU 2016)	(COEDD 2014) (BEA 2015) (World Bank Group 2016)
Comments	Projections for future years are based on data trends from 1964 to 2014.	Based on average temperature data for closest non-urban station to Orlando ("Clermont 9 S"). Projections for future years are based on data trends from 1964 to 2014.	GDP and its growth rates were estimated based on the most region-specific data available in any given year.

Model Parameter(s)	*Total Land Area & Land Expansion Rate*	*Population & Population Change Rate*	*Solar Research Cell Efficiency & Solar PV Research*
Lookup Data Source(s)	(COEDD 2014)	(COEDD 2014)	(NREL 2016a)
Comments	Expansion rates were estimated based on Orlando's historical and projected land area.	Population growth rates were estimated based on Orlando's historical and projected population.	Solar PV efficiency increase rate was estimated based on the average efficiencies of mono- and poly-crystalline solar PV cells.

Table D2: Model Parameter Formulas – Land Expansion Sub-Model

Model Parameter	*Land Expansion*	*Undeveloped Land Area*
Parameter Formula	$(Total\ Land\ Area) * (Land\ Expansion\ Rate)$	$IF\ THEN\ ELSE\left(\left(\sum_{l=1}^{4} A_l\right) > A_T,\ A_T - \left(\sum_{l=1}^{4} A_l\right),\ 0\right)$
Comments	Inflow for "Total Land Area".	"A_l" is the total area of roof type "l" (Set "l", indexed on "L"), and "A_T" is the total land area. The "IF THEN ELSE" function in this formula ensures that this parameter can never have a negative value by automatically setting the value to zero in such a case.

Figure D1: Land Expansion Sub-Model

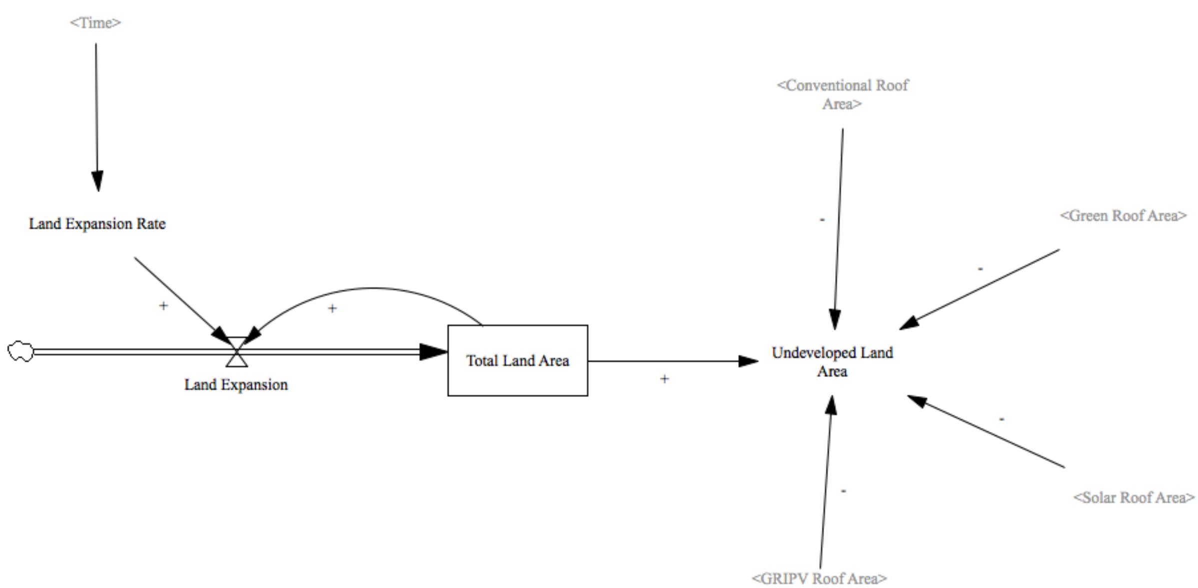


Table D3: Constant Parameter Values & Sources – Main Diffusion Model

Model Parameter	*Initial Population*	*Residential Roof Area*	*Household Size*	*Non-Residential Construction*
Constant Value	146,491 persons	0.034 acres/household	2.4 persons/household	5.985
Sources & Comments	(COEDD 2014)	(Huber 2016) 1,500 ft^2/household	(USCB 2016)	This value was estimated based on reference modes for "Total Runoff" and "Actual Air Temperature Anomaly".

Model Parameter	*Solar Advert Effect*	*Green Roof Intro Year*	*GRIPV Intro Year*
Constant Value	2.691×10^{-6}	2004	2020
Sources & Comments	Orlando's cumulative solar PV power capacity was 2 MW in 2013 (Burr et al. 2014), so this value was selected accordingly.	Orlando's first green roof was completed in 2005 (Greenroofs.com 2017d), so this value was selected accordingly.	This year was selected for purposes of the upcoming exploratory analyses.

Table D4: Model Parameter Formulas – Main Diffusion Model

Model Parameter	*Initial Roof Area*	*New Roofing Construction*
Parameter Formula	$(Initial\ Population) * (Household\ Size) * (Residential\ Roof\ Area) * (Non-Residential\ Construction)$	$(Population\ Change) * (Household\ Size) * (Residential\ Roof\ Area) * (Non-Residential\ Construction)$
Comments		This is assumed to be the sole inflow for "Conventional Roof Area".

Model Parameter	*Green Roof Market Switch*	*Green Advert Effect*
Parameter Formula	$STEP(1, Green\ Roof\ Intro\ Year)$	$(1.0725 \times 10^{-6}) * (Green\ Roof\ Market\ Switch)$
Comments	The "STEP" function in this formula is used to start green roof adoption on the designated introduction year (Table D3).	The coefficient of this equation was estimated based on reference mode data for "Green Roof Area". The parameter "Green Roof Market Switch" is used to start green roof adoption on the designated introduction year (Table D3).

Model Parameter	*Adoption Rate*	*Advert Adoption*
Parameter Formula	$(Advert\ Adoption) + (WOM\ Adoption)$	$(Conventional\ Roof\ Area) * (Advert\ Effect)$
Comments	This formula is exactly the same for all three alternative roofing inflows ("Green Adoption Rate", "Solar Adoption Rate", and "Direct GRIPV Adoption Rate"), and adoption between alternatives is ignored.	This formula is exactly the same for all three "Advert Adoption" parameters ("Green Advert Adoption", "Solar Advert Adoption", and "GRIPV Advert Adoption"), and adoption between alternatives is ignored.

Figure D2: Main Diffusion Model

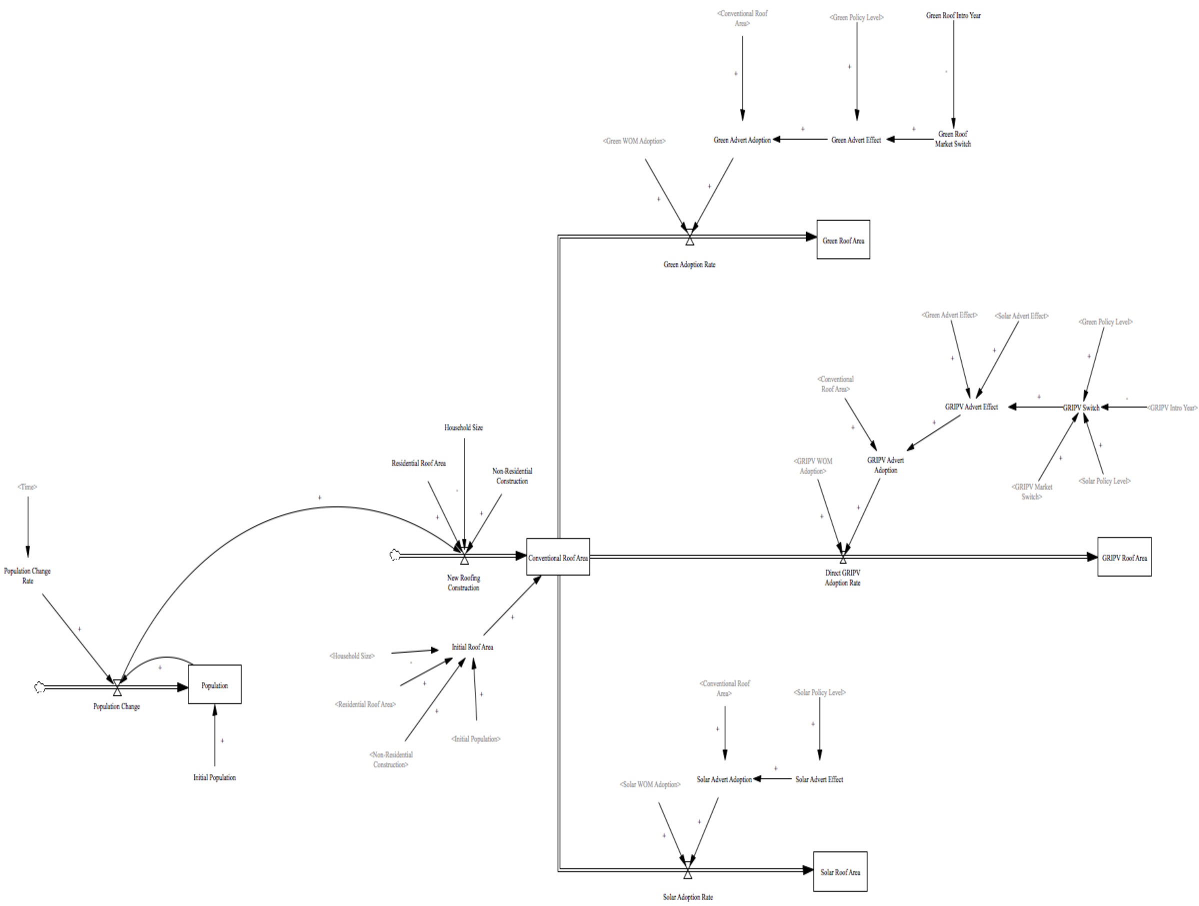


Table D5: Constant Parameter Values & Sources – Word-of-Mouth Sub-Model

Model Parameter	*Alt Roofing Contact Rate*	*Base Green Purchase Fraction*	*Base Solar Purchase Fraction*
Constant Value	100 per year	0.0012	0.0034
Sources & Comments	This value was estimated based on reference mode data for “Green Roof Area” and other relevant market penetration data (Burr et al. 2014).	This value was estimated based on reference mode data for “Green Roof Area”.	Orlando’s cumulative solar PV power capacity was 2 MW in 2013 (Burr et al. 2014), so this value was selected accordingly.

Table D6: Model Parameter Formulas – Word-of-Mouth Sub-Model

Model Parameter	*Alt Roofing Demand*
Parameter Formula	$\frac{(Urban\ Runoff\ Concerns) * (UHI\ Concerns) * (FGS)}{1 + (ETP + EGP) + (GTP + GGP)}$
Comments	FGS = Feasibility of Government Support ETP = Energy Target Progress EGP = Energy Goal Progress GTP = GHG Target Progress GGP = GHG Goal Progress Adding 1 in the denominator ensures that this formula never divides by zero.

Model Parameter	*Relative Attractiveness*
Parameter Formula	$(Practicality)_i * (Cost\ Effectiveness)_i$
Comments	This formula is exactly the same for all three “Relative Attractiveness” parameters (“Relative Green Attractiveness”, “Relative Solar Attractiveness”, and “Relative GRIPV Attractiveness”). “i” is the set of alternative roof types, indexed on “I”.

Model Parameter	*WOM Adoption*
Parameter Formula	$CR_{Alt} * BPF_i * ARD * RA_i * \left(\frac{A_{Conv} * A_i}{A_{Conv} + A_i}\right)$
Comments	This formula is exactly the same for all three “WOM Adoption” parameters (“Green WOM Adoption”, “Solar WOM Adoption”, and “GRIPV WOM Adoption”). CR_{Alt} = Alt Roofing Contact Rate BPF = Base Purchase Fraction ARD = Alt Roofing Demand RA = Relative Attractiveness A_{Conv} = Conventional Roof Area A = Roof Area “i” is the set of alternative roof types, indexed on “I”.

Model Parameter	*Base GRIPV Purchase Fraction*
Parameter Formula	$\frac{(Base\ Green\ Purchase\ Fraction) * (Base\ Solar\ Purchase\ Fraction)}{(Base\ Green\ Purchase\ Fraction) + (Base\ Solar\ Purchase\ Fraction)}$
Comments	This purchase fraction is assumed to be proportional to those of the green and solar roofing markets.

Figure D3: Word-of-Mouth Sub-Model – Main Structure

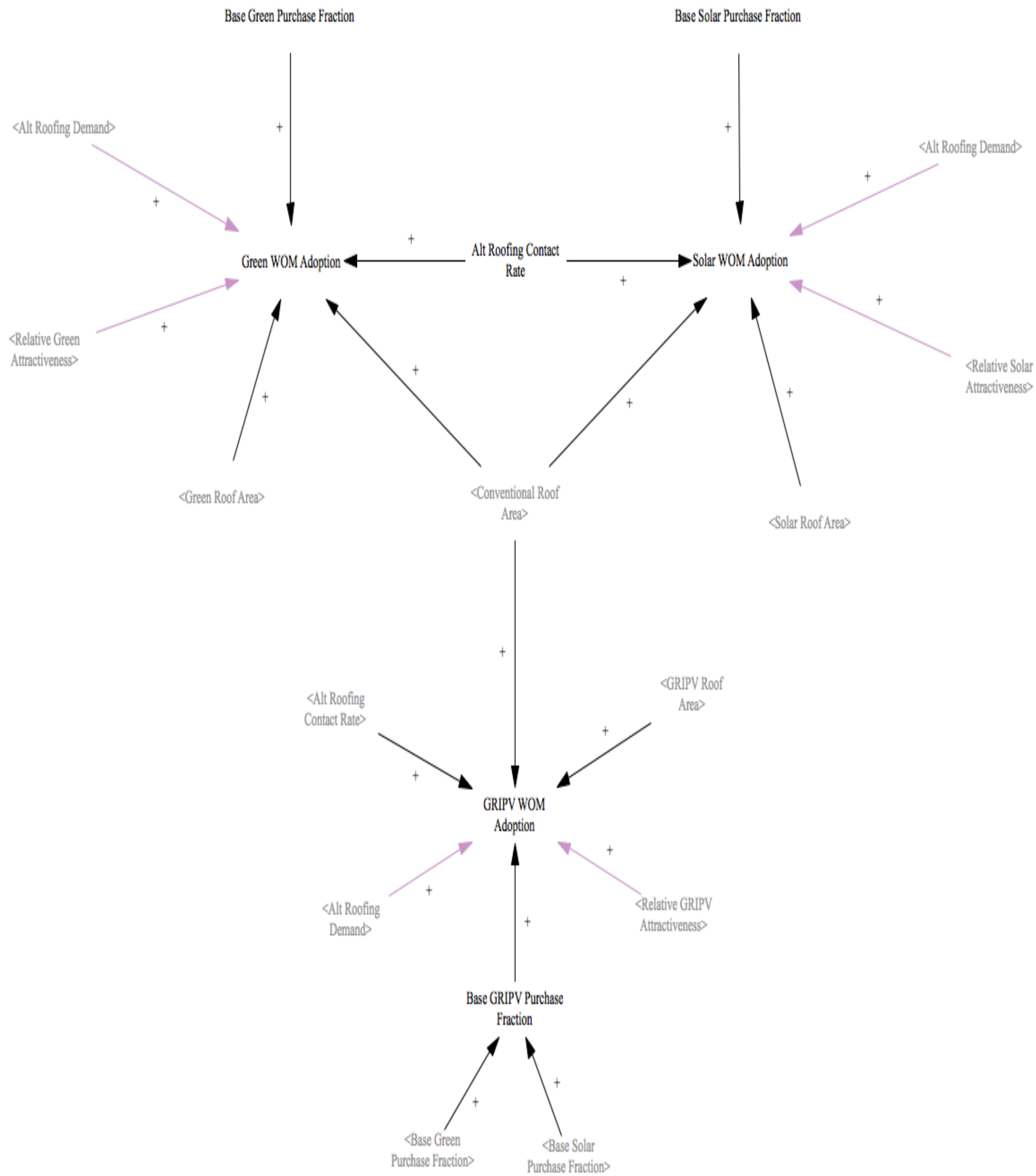


Figure D4: Word-of-Mouth Sub-Model – Demand & Attractiveness

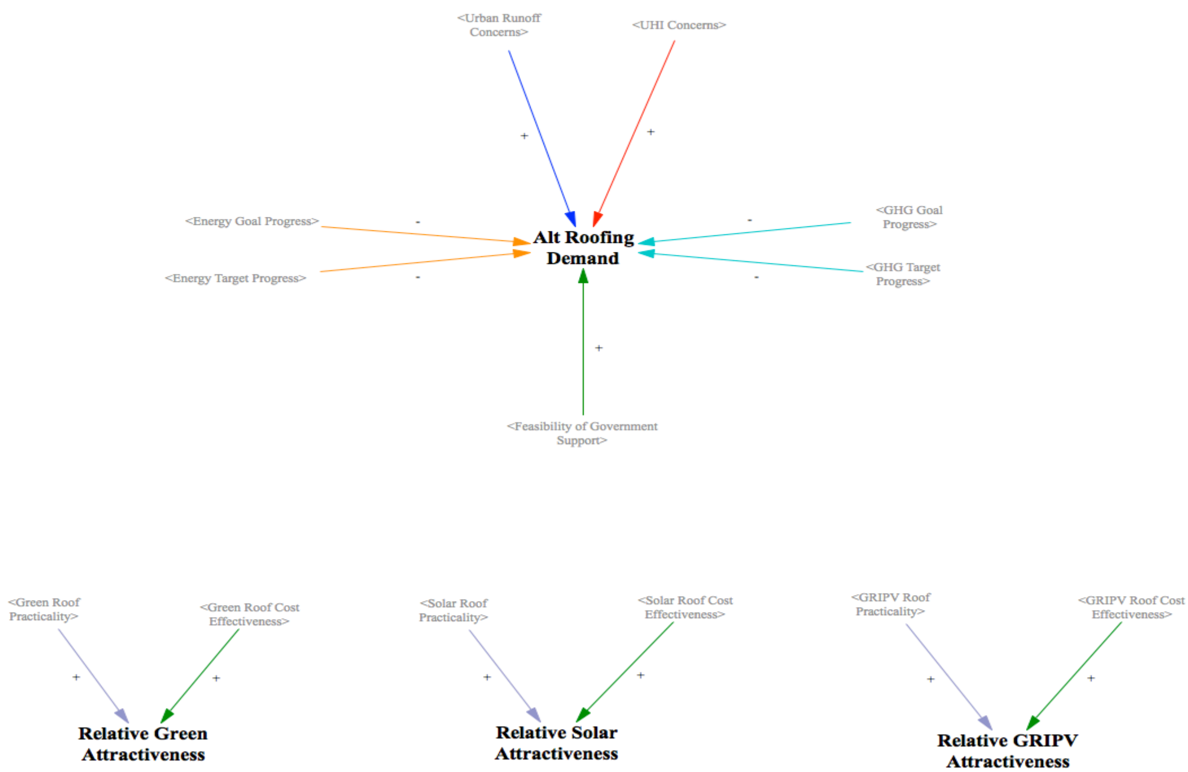


Table D7: Constant Parameter Values & Sources – Urban Runoff Sub-Model

Model Parameter	*Impervious ASRC*	*Pervious ASRC*	*Green Roof Annual Retention/ET Efficiency*
Constant Value	0.72	0.095	0.59233
Sources & Comments	See Table 3 in Section 1.1.9.1. This coefficient applies to conventional and solar roofing.	See Table 3 in Section 1.1.9.1. This coefficient applies to undeveloped land.	This was the average of the literature data (Table A1) and the relevant case study data point specified in Appendix C. This coefficient applies to green and GRIPV roofing.

Table D8: Model Parameter Formulas – Urban Runoff Sub-Model

Model Parameter	*Overall ASRC*	*Total Runoff*	*Base Runoff*	*Urban Runoff Concerns*
Parameter Formula	$\frac{\sum_{j=1}^{5}\left((A_j) * (ASRC_j)\right)}{\sum_{j=1}^{5}(A_j)}$	$(Total\ Rainfall) * (Overall\ ASRC)$	$(Total\ Rainfall) * (Pervious\ ASRC)$	$\frac{Total\ Runoff}{Base\ Runoff}$
Comments	"j" is the set of all developed and undeveloped surface types, indexed on "J".			

Figure D5: Urban Runoff Sub-Model

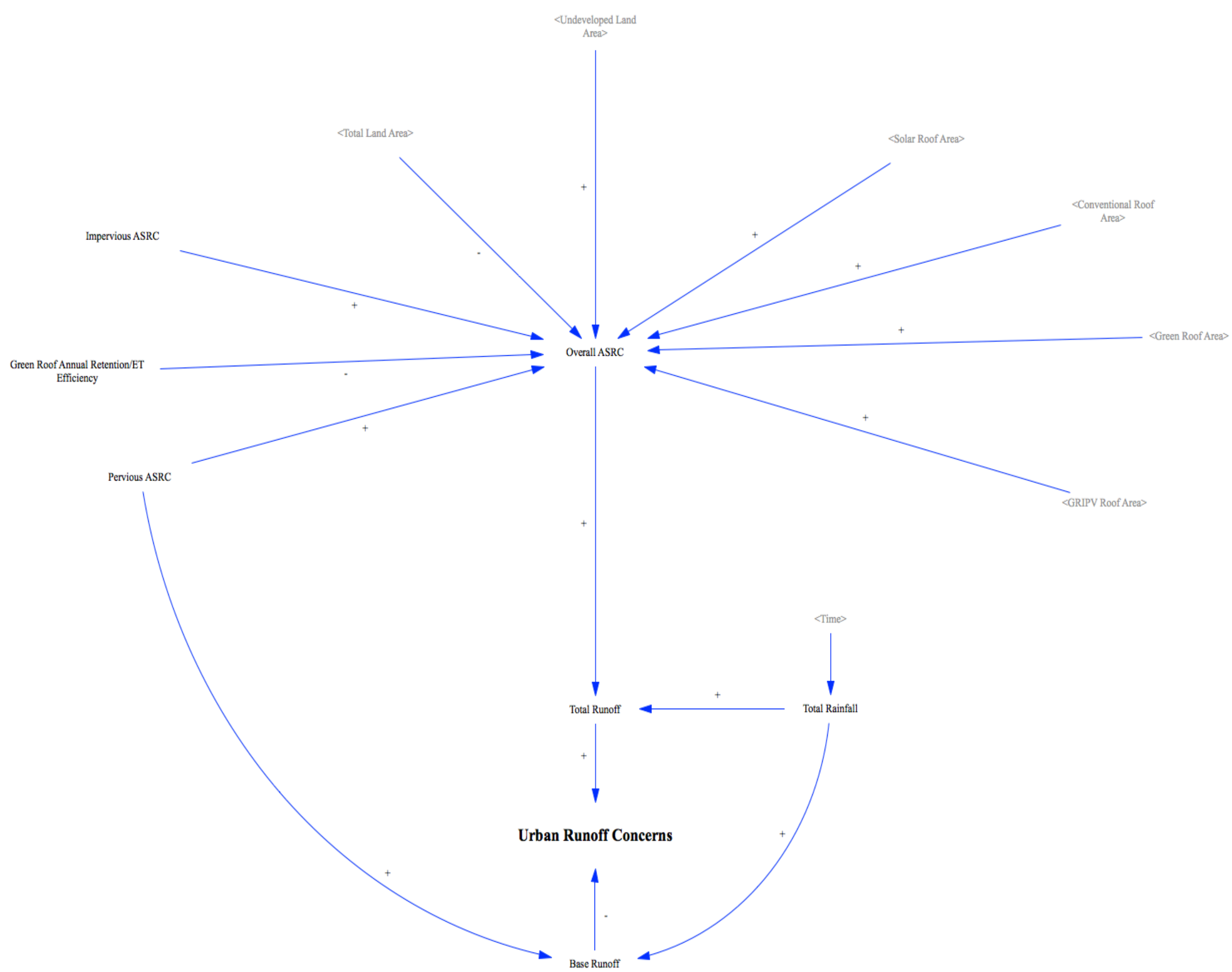


Table D9: Constant Parameter Values & Sources – Urban Heat Island Sub-Model

Model Parameter	*Conventional Roof Albedo*	*Plant Albedo*	*Solar Panel Albedo*
Constant Value	0.1142	0.303	0.164
Sources & Comments	This was the average of the literature data (Table A2).	This was the average of the literature data (Table A2). This coefficient applies to undeveloped land and green roofing.	This was the average of the literature data (Table A2).

Model Parameter	*Cooling Via Evapotranspiration*	*Average Total Horizontal Insolation*	*Surface-to-Air UHI Temperature Ratio*
Constant Value	0.375	0.474 kWh/(ft^2-day)	8
Sources & Comments	This was the average of the literature data (Table A2).	This value was derived from Table 4 in Section 1.1.9.1 and converted to appropriate units.	This value was estimated based on reference mode data for "Actual Air Temperature Anomaly" and is consistent with applicable data ranges (EPA 2008).

Table D10: Physical Constants of Conventional & Solar Roofs – Urban Heat Island Sub-Model

Model Parameter	*Conventional Roof Thickness*	*Conventional Roof Density*	*Conventional Roof Specific Heat*	*Solar Panel Specific Heat*
Constant Value	0.99 ft	36.5 kg/ft^3	4.59×10^{-4} kWh/(kg*^{0}F)	4.95×10^{-4} kWh/(kg*^{0}F)
Sources & Comments	This is the average of total thickness data from the literature (Lazzarin et al. 2005; Wang et al. 2006).	This is the average of the average density data from the literature (Lazzarin et al. 2005; Wang et al. 2006).	This is the average of the average specific heat data from the literature (Lazzarin et al. 2005; Wang et al. 2006).	(Wang et al. 2006) Solar panel density and thickness are both subject to learning curves (Table D23).

Table D11: Physical Constants of Green Roofs – Urban Heat Island Sub-Model

Model Parameter	*Green Roof Thickness*	*Green Roof Density*	*Green Roof Specific Heat*
Constant Value	1.56 ft	39.8 kg/ft^3	$4.69x10^{-4}$ $kWh/(kg*^0F)$
Sources & Comments	This value is based on the total thickness data from the literature (Capozzoli et al. 2013), accounting for variations in soil/media depth from real green roofs in Orlando (Table C1).	This value is based on the physical property data ranges from the literature (Capozzoli et al. 2013).	This value is based on the physical property data ranges from the literature (Capozzoli et al. 2013).

Table D12: Physical Constants of GRIPV Roofs – Urban Heat Island Sub-Model

Model Parameter	*GRIPV Green Thickness*	*GRIPV Green Density*	*GRIPV Green Specific Heat*
Constant Value	1.33 ft	41.14 kg/ft^3	$4.62x10^{-4}$ $kWh/(kg*^0F)$
Sources & Comments	See Table C4.	See Table C4.	See Table C4.

Table D13: Physical Constants of Undeveloped Land – Urban Heat Island Sub-Model

Model Parameter	*Minimum Natural Soil Depth*	*Undeveloped Soil Density*	*Undeveloped Soil Specific Heat*
Constant Value	7.33 ft	30.89 kg/ft^3	$4.62x10^{-4}$ $kWh/(kg*^0F)$
Sources & Comments	This is the maximum pedon depth of Orlando Series soil (USDA 2001).	This value is the average of all soil/media data values provided in the available literature (Capozzoli et al. 2013).	This value is the average of all soil/media data values provided in the available literature (Capozzoli et al. 2013).

Table D14: Cooling Effect Formulas – Urban Heat Island Sub-Model

Model Parameter	*Solar Roof Cooling Effect*	*Cooling Effect of Vegetation*
Parameter Formula	$(Solar\ Panel\ Albedo) + (Solar\ PV\ Commercial\ Efficiency)$	$(Plant\ Albedo) + (Cooling\ Via\ Evapotranspiration)$
Comments	"Solar PV Commercial Efficiency" will be discussed in Table D18.	This cooling effect applies to green roofs and undeveloped land.

Model Parameter	*GRIPV Roof Cooling Effect*
Parameter Formula	$ET + \left((GOF) * (Alb_{Plant})\right) + \left((SC) * (Alb_{Solar} + (\eta_{PV})_{GRIPV})\right)$
Comments	ET = Cooling Via Evapotranspiration GOF = GRIPV Green Only Fraction (See Table D39) Alb_{Plant} = Plant Albedo SC = GRIPV Solar Coverage (See Table D38) Alb_{Solar} = Solar Panel Albedo $(\eta_{PV})_{GRIPV}$ = GRIPV Solar Energy Efficiency (Table D19)

Figure D6: Urban Heat Island Sub-Model – Cooling Effects

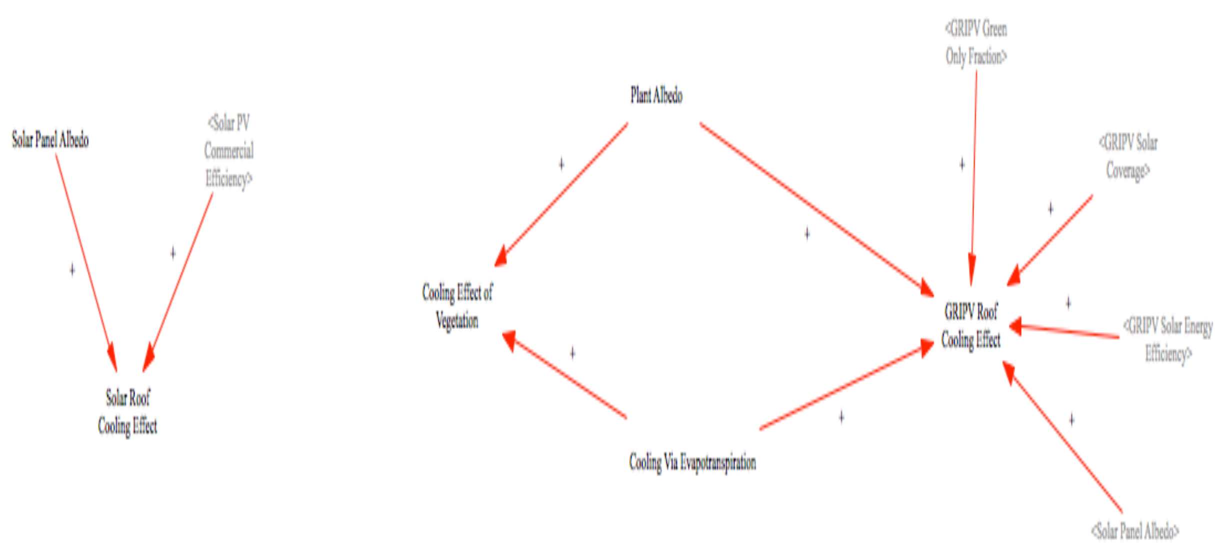


Table D15: Physical Formulas of Solar & GRIPV Roofs – Urban Heat Island Sub-Model

Model Parameter	*Solar Roof Thickness*	*GRIPV Roof Thickness*
Parameter Formula	$t_{Panel} + t_{Conv}$	$(GOF)(t_{GG})$ $+$ $(SC)(t_{Panel} + t_{GG})$
Comments	t_{Panel} = Solar Panel Thickness (See Table D35) t_{Conv} = Conventional Roof Thickness	GOF = GRIPV Green Only Fraction (See Table D39) t_{GG} = GRIPV Green Thickness

Model Parameter	*Solar Roof Density*	*GRIPV Roof Density*
Parameter Formula	$\frac{(\rho_{Panel})(t_{Panel}) + (\rho_{Conv})(t_{Conv})}{t_{Panel} + t_{Conv}}$	$(GOF)(\rho_{GG})$ $+$ $(SC)\left(\frac{(\rho_{Panel})(t_{Panel}) + (\rho_{GG})(t_{GG})}{t_{Panel} + t_{GG}}\right)$
Comments	ρ_{Panel} = Solar Panel Density (See Table D35) ρ_{Conv} = Conventional Roof Density	SC = GRIPV Solar Coverage (See Table D38) ρ_{GG} = GRIPV Green Density

Model Parameter	*Solar Roof Specific Heat*	*Solar Roof Specific Heat*
Parameter Formula	$\frac{(c_{Panel})(t_{Panel}) + (c_{Conv})(t_{Conv})}{t_{Panel} + t_{Conv}}$	$(GOF)(c_{GG})$ $+$ $(SC)\left(\frac{(c_{Panel})(t_{Panel}) + (c_{GG})(t_{GG})}{t_{Panel} + t_{GG}}\right)$
Comments	c_{Panel} = Solar Panel Specific Heat c_{Conv} = Conventional Roof Specific Heat	c_{GG} = GRIPV Green Specific Heat

Table D16: Surface Temperature Formulas – Urban Heat Island Sub-Model

Model Parameter	*Surface Temp Change*	*Night-to-Day Surface Temp Change*
Parameter Formula	$\frac{(ATHI)(1 - Cool_j)(1\ day)}{(t_j)(\rho_j)(c_j)}$	$\frac{\sum_{j=1}^{5}\left(\left(\Delta T_{Surface}\right)_j (A_j)\right)}{\sum_{j=1}^{5}(A_j)}$
Comments	"j" is the set of all developed and undeveloped surface types, indexed on "J". ATHI = Average Total Horizontal Insolation Cool = Cooling Effect ($Cool_{Conv}$ = Conventional Roof Albedo) t = Surface Thickness ρ = Surface Density c = Surface Specific Heat ATHI is measured per day, so this formula is multiplied by "1 day" to reflect the daily temperature change.	$(\Delta T_{Surface})_j$ = Surface Temp Change of Surface Type "j" A_j = Area of Surface Type "j"

Model Parameter	*Base Surface Temp Change*
Parameter Formula	$\frac{(ATHI)(1 - Cool_{Undev})(1\ day)}{(t_{Undev})(\rho_{Undev})(c_{Undev})}$
Comments	ATHI = Average Total Horizontal Insolation $Cool_{Undev}$ = Cooling Effect of Vegetation t_{Undev} = Minimum Natural Soil Depth ρ_{Undev} = Undeveloped Soil Density c_{Undev} = Undeveloped Soil Specific Heat ATHI is measured per day, so this formula is multiplied by "1 day" to reflect the night-to-day temperature change.

Figure D7: Urban Heat Island Sub-Model – Surface Temperature Change

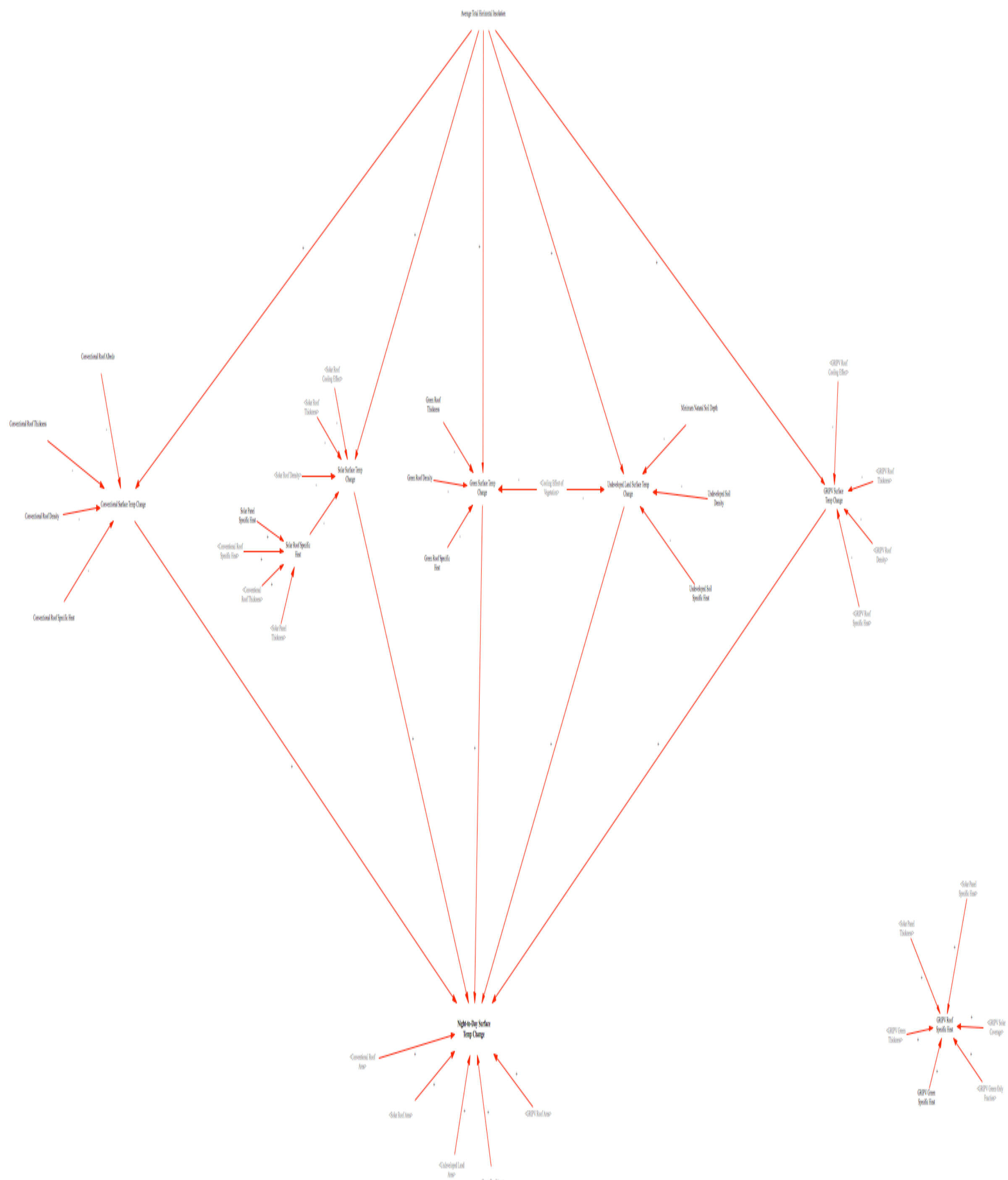


Table D17: Temperature Anomaly & UHI Concern Formulas – Urban Heat Island Sub-Model

Model Parameter	*Surface Temperature Anomaly*	*Actual Air Temperature Anomaly*	*Perceived Air Temperature Anomaly*
Parameter Formula	$\Delta T_{Overall}$ - ΔT_{Base}	$\frac{STA}{R_{S/A}}$	$SMOOTH3(ATA_{Actual}, 2)$
Comments	$\Delta T_{Overall}$ = Night-to-Day Surface Temp Change ΔT_{Base} = Base Surface Temp Change	STA = Surface Temperature Anomaly $R_{S/A}$ = Surface-to-Air UHI Temperature Ratio	The "SMOOTH3" function in this formula is used to simulate a 3rd-Order, 2-year information delay. ATA_{Actual} = Actual Air Temperature Anomaly

Model Parameter	*UHI Concerns*
Parameter Formula	$\frac{ATA_{Perceived}}{T_{Rural}}$
Comments	$ATA_{Perceived}$ = Perceived Air Temperature Anomaly T_{Rural} = Average Rural Air Temperature

Figure D8: Urban Heat Island Sub-Model – Temperature Anomalies

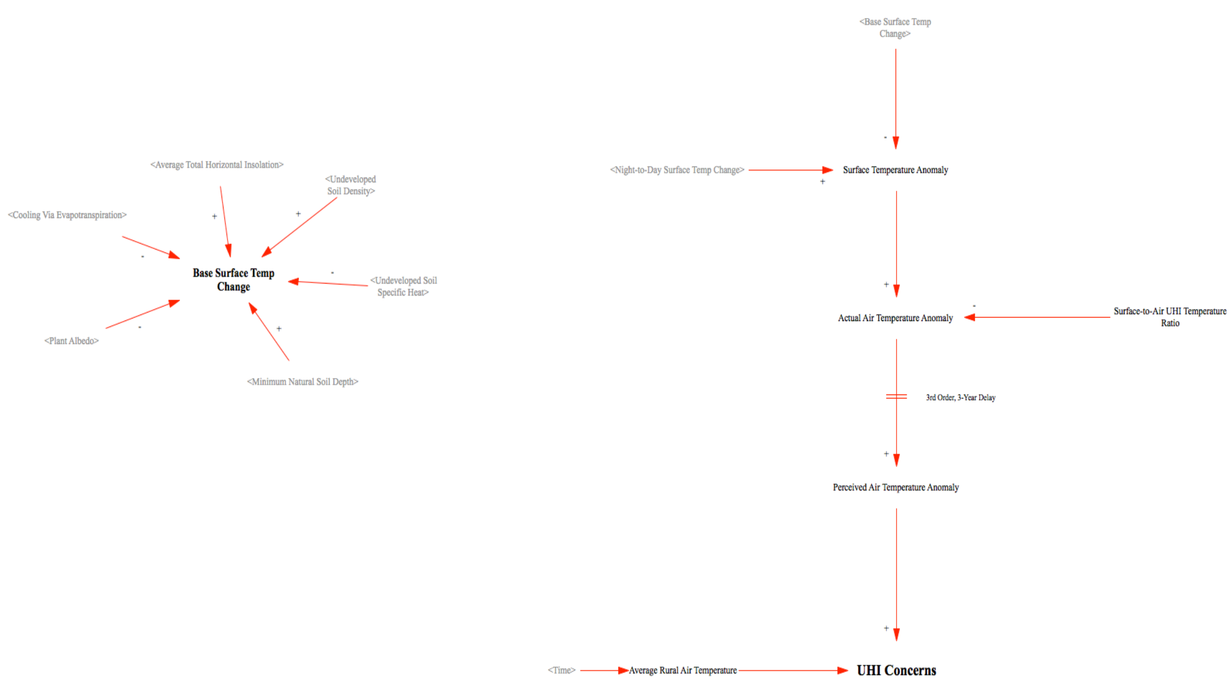


Table D18: Constant Parameter Values & Sources – Energy Sub-Model

Model Parameter	*Green Cooling Load Reduction Per Acre*	*Solar Cooling Load Reduction Per Acre*	*Annual Sun Hours*
Constant Value	3.97 kW/Acre	12.94 kW/acre	1,821.35 hours/year
Sources & Comments	This value is based on the average difference between green and conventional cooling loads from the literature data (Table A3).	This value is based on the average difference between solar and conventional cooling loads from the literature data (Table A3).	See Table 6 in Section 1.1.9.3.

Model Parameter	*Solar Power Capacity Per Acre*	*GRIPV Solar Energy Improvement*	*Energy Demand Per Capita in 2010*
Constant Value	613.272 kW/Acre	0.0373 (3.73%)	12,003 kWh/person
Sources & Comments	This was the average of the available data on actual roof-mounted solar PV arrays in Orlando (Table C2).	This was the average of the literature data (Table A8).	See Table 5 in Section 1.1.9.3.

Model Parameter	*2018 Energy Demand Reduction Target*	*2040 Energy Demand Reduction Goal*
Constant Value	0.05 (5%)	0.2 (20%)
Sources & Comments	See Table 5 in Section 1.1.9.3.	See Table 5 in Section 1.1.9.3.

Table D19: Energy Efficiency Formulas – Energy Sub-Model

Model Parameter	*Solar PV Development*	*Solar PV Commercial Efficiency*
Parameter Formula	$(Solar\ PV\ Research) * (Solar\ Research\ Cell\ Efficiency)$	$0.627662 * (Solar\ Research\ Cell\ Efficiency)$
Comments	This is the sole inflow for "Solar Research Cell Efficiency".	The coefficient of this formula is based on the past ratio of research cell efficiency to commercial module efficiency (DOE 2011). This energy efficiency (η) applies to solar roofing.

Model Parameter	*GRIPV Solar Energy Efficiency*
Parameter Formula	$(Solar\ PV\ Commercial\ Efficiency) * (1 + GRIPV\ Solar\ Energy\ Improvement)$
Comments	This energy efficiency (η) applies to GRIPV roofing.

Table D20: Energy Demand Reduction Formulas – Energy Sub-Model

Model Parameter	*Green Energy Demand Reduction*	*Solar Energy Demand Reduction*
Parameter Formula	$(h_{Sun})(cl_{Green})(A_{Green})$	$(h_{Sun})(cl_{Solar})(A_{Solar}) + (h_{Sun})(\eta_{Solar})(p_{Solar})(A_{Solar})$
Comments	h_{Sun} = Annual Sun Hours cl_{Green} = Green Cooling Load Reduction Per Acre A_{Green} = Green Roof Area	h_{Sun} = Annual Sun Hours cl_{Solar} = Solar Cooling Load Reduction Per Acre η_{Solar} = Solar PV Commercial Efficiency p_{Solar} = Solar Power Capacity Per Acre A_{Solar} = Solar Roof Area

Model Parameter	*GRIPV Cooling Load Reduction Per Acre*	*GRIPV Energy Demand Reduction*
Parameter Formula	$(GOF * cl_{Green}) + \big(SC * (cl_{Green} + cl_{Solar})\big)$	$A_{GRIPV} * h_{Sun} * \big(cl_{GRIPV} + (\eta_{Solar})(p_{Solar})(SC)\big)$
Comments	GOF = GRIPV Green Only Fraction (See Table D39) SC = GRIPV Solar Coverage (See Table D38) cl_{Green} = Green Cooling Load Reduction Per Acre cl_{Solar} = Solar Cooling Load Reduction Per Acre	A_{GRIPV} = GRIPV Roof Area h_{Sun} = Annual Sun Hours cl_{GRIPV} = GRIPV Cooling Load Reduction Per Acre η_{GRIPV} = GRIPV Solar Energy Efficiency p_{Solar} = Solar Power Capacity Per Acre SC = GRIPV Solar Coverage (See Table D38)

Table D21: Total Energy Savings Formulas – Energy Sub-Model

Model Parameter	*Total Reduced Energy Demand*	*Energy Demand Savings Per Capita*
Parameter Formula	$EDR_{Green} + EDR_{Solar} + EDR_{GRIPV}$	$\frac{EDR_{Total}}{Population}$
Comments	EDR_{Green} = Green Energy Demand Reduction EDR_{Solar} = Solar Energy Demand Reduction EDR_{GRIPV} = GRIPV Energy Demand Reduction	EDR_{Total} = Total Reduced Energy Demand

Model Parameter	*Target Switch*	*Energy Target Progress*	*Goal Switch*	*Energy Goal Progress*
Parameter Formula	$STEP(1,2013) - STEP(1,2019)$	$TS * \left(\frac{EDR_{Cap}}{(ERT)(ED_{2010})}\right)$	$STEP(1,2018)$	$GS * \left(\frac{EDR_{Capita}}{(ERG)(ED_{2010})}\right)$
Comments	This switch is used to activate the “Target Progress” variables from 2013 to 2018, when these targets would be in effect (Green Works Orlando 2016).	TS = Target Switch EDR_{Capita} = Energy Demand Savings Per Capita ERT = 2018 Energy Demand Reduction Target ED_{2010} = Energy Demand Per Capita in 2010	This switch is used to activate the “Goal Progress” variables from 2018 onward, when these goals would be in effect (Green Works Orlando 2016).	GS = Goal Switch EDR_{Capita} = Energy Demand Savings Per Capita ERG = 2040 Energy Demand Reduction Goal ED_{2010} = Energy Demand Per Capita in 2010

Figure D9: Energy Sub-Model

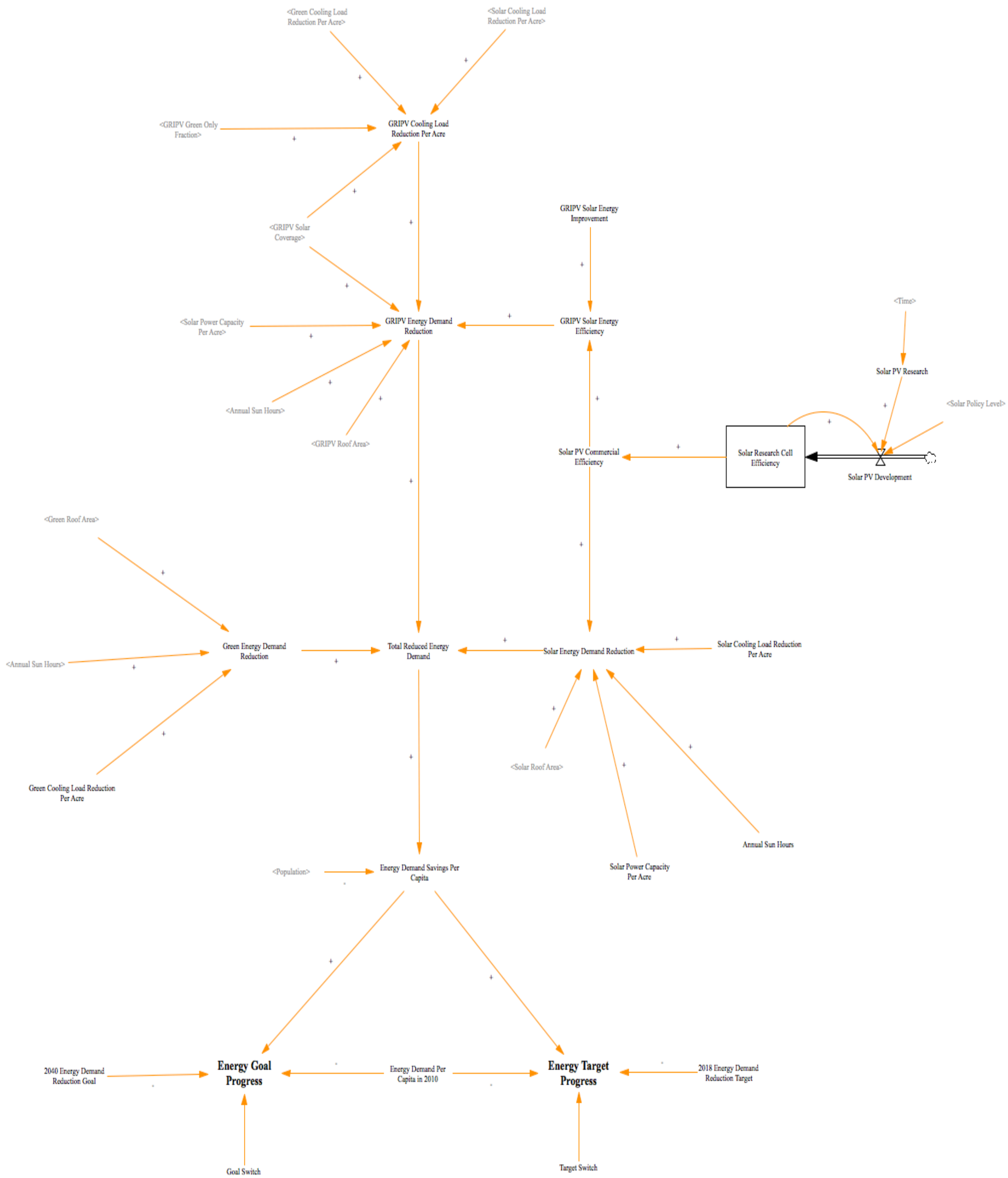


Table D22: Constant Parameter Values & Sources – GHG Sub-Model

Model Parameter	*Grid GHG Emission Factor*	*Green Carbon Sequestration*
Constant Value	$5.1\times10^{-4}\,\frac{Metric\ Tons\ CO_2}{kWh}$	$5.6\,\frac{Metric\ Tons\ CO_2}{Acre}$
Sources & Comments	See Table 7 in Section 1.1.9.4.	This was the average of the literature data (Table A4).

Model Parameter	*Total GHG Emissions in 2007*	*2018 GHG Reduction Target*	*2040 GHG Reduction Goal*
Constant Value	5.265×10^{6} $Metric\ Tons\ CO_2$	0.25 (25%)	0.9 (90%)
Sources & Comments	See Table 7 in Section 1.1.9.4.	See Table 7 in Section 1.1.9.4.	See Table 7 in Section 1.1.9.4.

Table D23: Model Parameter Formulas – GHG Sub-Model

Model Parameter	*Green GHG Reduction*	*Solar GHG Reduction*	*GRIPV GHG Reduction*
Parameter Formula	$(EDR_{Green})(EF_{Grid}) + (A_{Green})(CS_{Green})$	$(EDR_{Solar})(EF_{Grid})$	$(EDR_{GRIPV})(EF_{Grid}) + (VCG)(A_{GRIPV})(CS_{Green})$
Comments	EDR_{Green} = Green Energy Demand Reduction EF_{Grid} = Grid GHG Emission Factor A_{Green} = Green Roof Area CS_{Green} = Green Carbon Sequestration	EDR_{Green} = Green Energy Demand Reduction EDR_{Solar} = Solar Energy Demand Reduction EDR_{GRIPV} = GRIPV Energy Demand Reduction	EDR_{GRIPV} = GRIPV Energy Demand Reduction EF_{Grid} = Grid GHG Emission Factor A_{Green} = Green Roof Area CS_{Green} = Green Carbon Sequestration

Model Parameter	*Total Reduction in GHG*
Parameter Formula	$GR_{Green} + GR_{Solar} + GR_{GRIPV}$
Comments	GR_{Green} = Green GHG Reduction GR_{Solar} = Solar GHG Reduction GR_{GRIPV} = GRIPV GHG Reduction

Model Parameter	*Target Switch*	*GHG Target Progress*	*Goal Switch*	*GHG Goal Progress*
Parameter Formula	$STEP(1{,}2013) - STEP(1{,}2019)$	$TS * \left(\frac{GR_{Total}}{(GRT)(GR_{2007})}\right)$	$STEP(1{,}2018)$	$GS * \left(\frac{GR_{Total}}{(GRG)(GR_{2007})}\right)$
Comments	This switch is used to activate the "Target Progress" variables from 2013 to 2018, when these targets would be in effect (Green Works Orlando 2016).	TS = Target Switch GR_{Capita} = Total Reduction in GHG GRT = 2018 GHG Reduction Target GR_{2007} = Total GHG Emissions in 2007	This switch is used to activate the "Goal Progress" variables from 2018 onward, when these goals would be in effect (Green Works Orlando 2016).	GS = Goal Switch GR_{Capita} = Total Reduction in GHG GRG = 2040 GHG Reduction Goal GR_{2007} = Total GHG Emissions in 2007

Figure D10: GHG Sub-Model

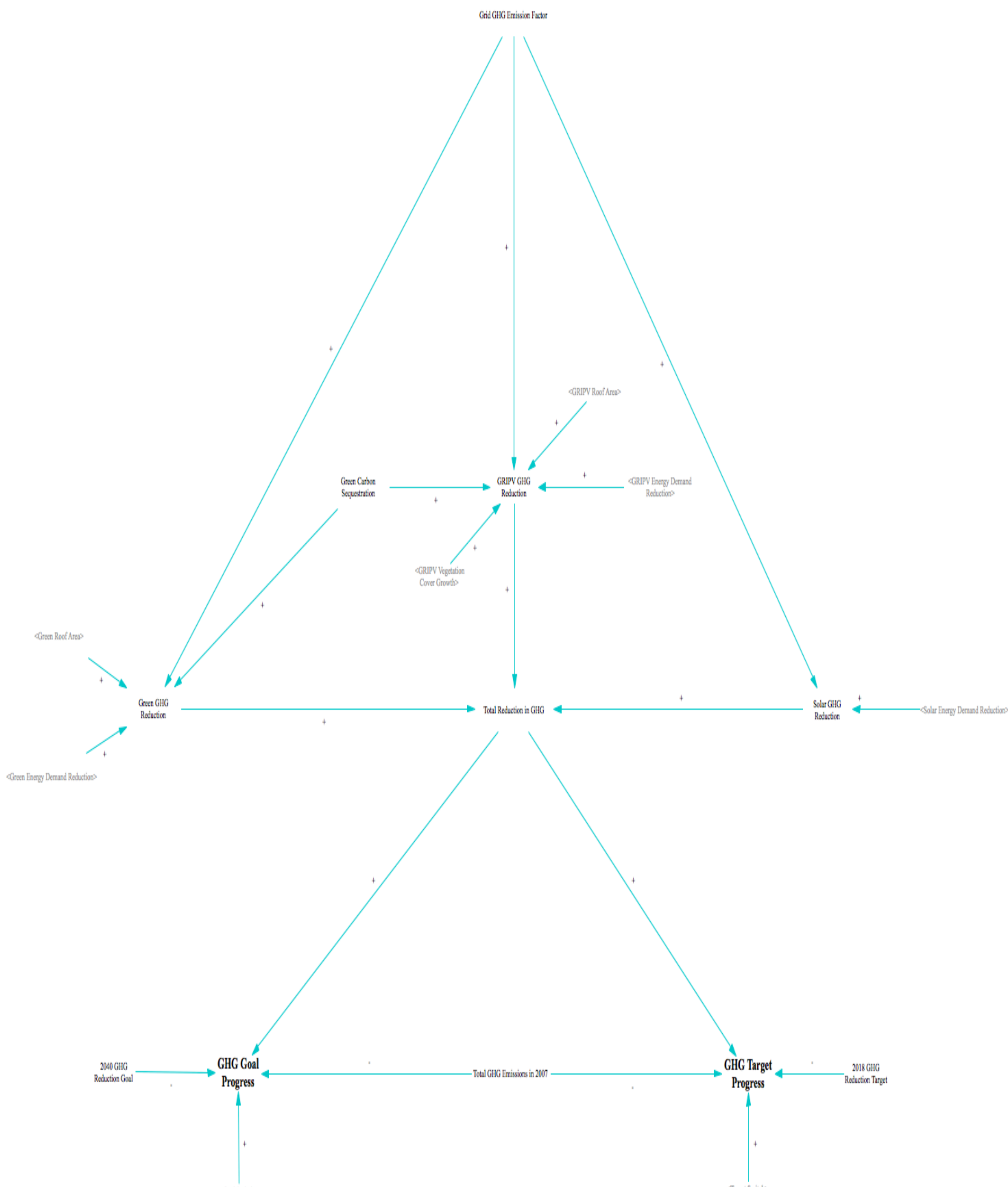


Table D24: Learning Curves – Economic Sub-Model

Time Period	*1985 to 2040*
Wastewater Costs (USD/Gallon)	$0.0027e^{(0.0147*(Time-1985))}$
Comments	This curve was estimated based on available data for past wastewater costs per gallon (OCU 2010; OCU 2016).

Time Period	*1985 to 2018*	*2019 to 2022*	*2023 to 2040*
Grid LCOE (USD/kWh)	$0.00226 * e^{(0.101*(Time-1985))}$	$0.07 * e^{(0.101*(Time-2018))}$	$0.09479 * e^{(-0.00217*(Time-2022))}$
Comments	These curves were estimated based on historical and projected LCOE data (NREL 2017).		

Time Period	*1985 to 2009*	*2010 to 2017*
Solar Total LCOE (USD /kWh)	$3.12533 * e^{(0.1108*(Time-1985))}$	$0.196 * e^{(0.1108*(Time-2010))}$
Comments	These curves were estimated based on historical and projected LCOE data (NREL 2017; DOE 2011).	

Time Period	*2018 to 2021*	*2022 to 2040*
Solar Total LCOE (USD /kWh)	$0.0808 * e^{(-0.0118*(Time-2018))}$	$0.0847 * e^{(0.0023*(Time-2022))}$
Comments	These curves were estimated based on historical and projected LCOE data (NREL 2017).	

Table D25: Financial Incentive Parameter Formulas – Economic Sub-Model

Model Parameter	*GDP Change*
Parameter Formula	$(GDP\ Change\ Rate) * (GDP)$
Comments	This is the sole inflow for "GDP".

Model Parameter	*Standardized Green Incentives*	*Standardized Solar Incentives*
Parameter Formula	$\frac{(GDP)(IF_{Green}) + PS_{Green}}{NC}$	$\frac{(GDP)(IF_{Solar}) + PS_{Solar}}{NC}$
Comments	IF_{Green} = Green GDP Investment Fraction PS_{Green} = Private Green Subsidies NC = New Roofing Construction "IF_{Green}" and "PS_{Green}" are both policy variables (See Tables F5 and F6).	IF_{Solar} = Solar GDP Investment Fraction PS_{Solar} = Private Solar Subsidies NC = New Roofing Construction "IF_{Solar}" and "PS_{Solar}" are both policy variables (See Table F5 and F6).

Model Parameter	*Standardized GRIPV Incentives*
Parameter Formula	$(Standardized\ Green\ Incentives) + (SC)(Standardized\ Solar\ Incentives)$
Comments	SC = GRIPV Solar Coverage (See Table D38)

Figure D11: Economic Sub-Model – Financial Incentives

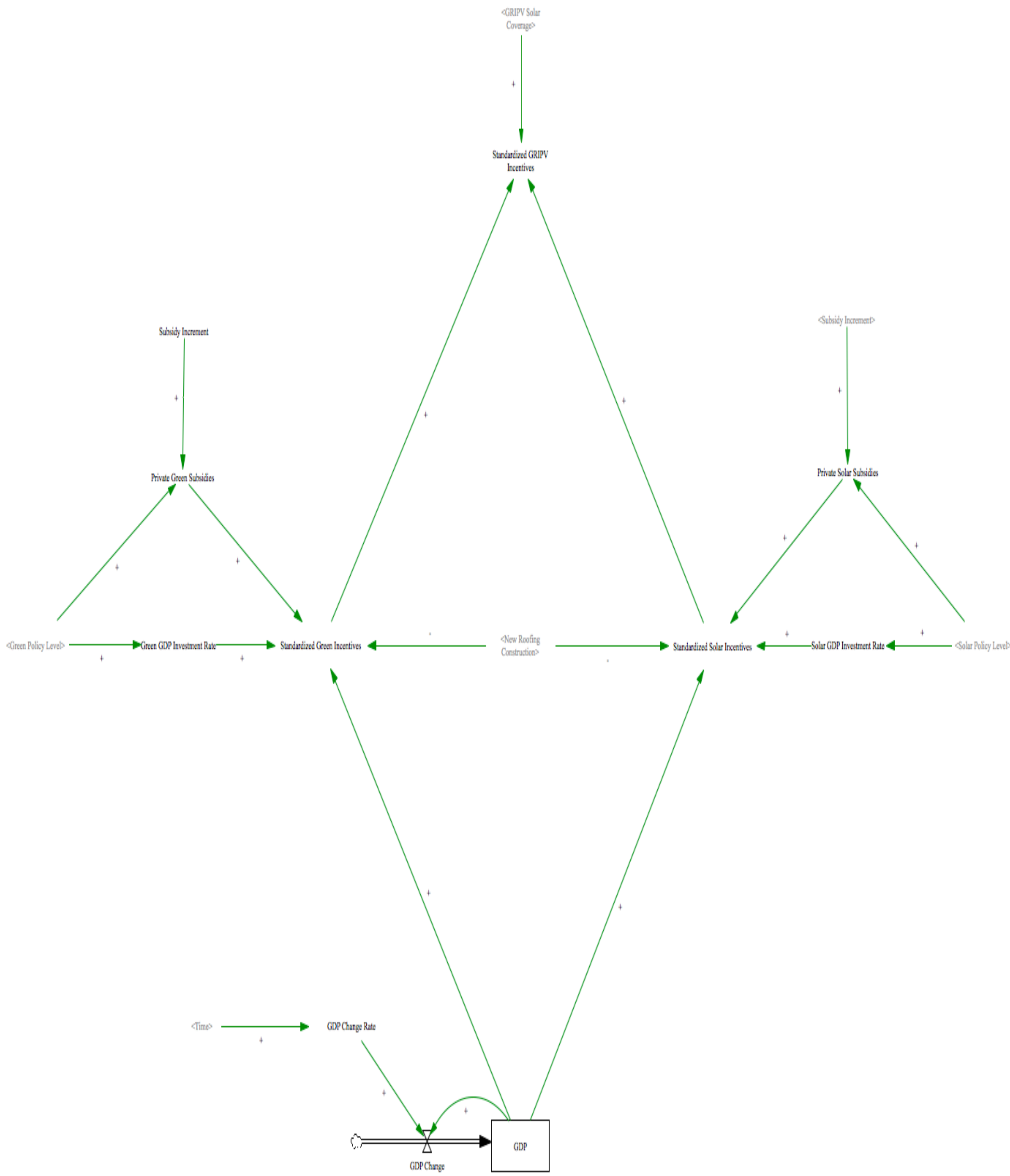


Table D26: Runoff Operational Savings Formulas – Economic Sub-Model

Model Parameter	*Green Rainfall Retention Volume*	*GRIPV Rainfall Retention Volume*
Parameter Formula	$(P) * (A_{Green}) * (1 - ASRC_{Green}) * \left(\frac{27{,}154\ gal}{acre * in}\right)$	$(P) * (A_{GRIPV}) * (1 - ASRC_{Green}) * \left(\frac{27{,}154\ gal}{acre * in}\right)$
Comments	P = Total Rainfall A_{Green} = Green Roof Area $(1\text{-}ASRC_{Green})$ = Green Roof Annual Retention/ET Efficiency Conversion Factor Included	P = Total Rainfall A_{GRIPV} = GRIPV Roof Area $(1\text{-}ASRC_{Green})$ = Green Roof Annual Retention/ET Efficiency Conversion Factor Included

Model Parameter	*Green Runoff Savings*	*GRIPV Runoff Savings*
Parameter Formula	$(C_{WW}) * (RV_{Green})$	$(C_{WW}) * (RV_{GRIPV})$
Comments	C_{WW} = Wastewater Costs RV_{Green} = Green Rainfall Retention Volume	C_{WW} = Wastewater Costs RV_{GRIPV} = Green Rainfall Retention Volume

Table D27: Energy Operational Savings Formulas – Economic Sub-Model

Model Parameter	*Green Roof Energy Savings*	*Solar Roof Energy Savings*	*GRIPV Energy Savings*
Parameter Formula	$EDR_{Green} * LCOE_{Grid}$	$EDR_{Solar} * LCOE_{Grid}$	$EDR_{GRIPV} * LCOE_{Grid}$
Comments	EDR_{Green} = Green Energy Demand Reduction $LCOE_{Grid}$ = Grid LCOE	EDR_{Solar} = Solar Energy Demand Reduction $LCOE_{Grid}$ = Grid LCOE	EDR_{GRIPV} = GRIPV Energy Demand Reduction $LCOE_{Grid}$ = Grid LCOE

Table D28: Standardized Operational Savings Formulas – Economic Sub-Model

Model Parameter	*Green Operational Savings*	*GRIPV Operational Savings*
Parameter Formula	$(Green\ Runoff\ Savings) + (Green\ Roof\ Energy\ Savings)$	$(GRIPV\ Runoff\ Savings) + (GRIPV\ Energy\ Savings)$
Comments		

Model Parameter	*Standardized Green Op Savings*	*Standardized Solar Op Savings*	*Standardized GRIPV Op Savings*
Parameter Formula	$\frac{OS_{Green}}{A_{Green}}$	$\frac{ES_{Solar}}{A_{Solar}}$	$\frac{OS_{GRIPV}}{A_{GRIPV}}$
Comments	OS_{Green} = Green Operational Savings A_{Green} = Green Roof Area	ES_{Solar} = Solar Roof Energy Savings A_{Solar} = Solar Roof Area	OS_{GRIPV} = GRIPV Operational Savings A_{GRIPV} = GRIPV Roof Area

Figure D12: Economic Sub-Model – Operational Savings

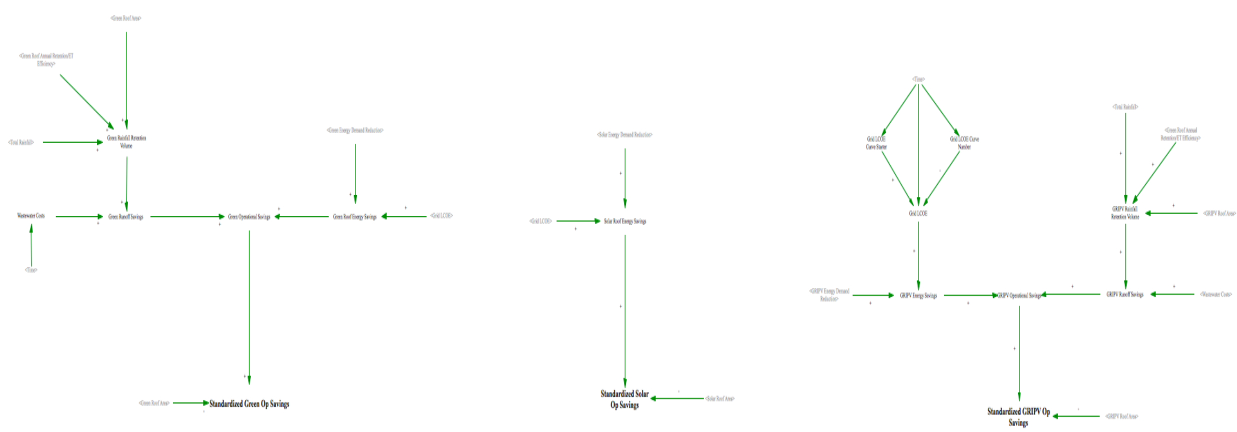


Table D29: Gross Cost Constant Parameter Values & Sources – Economic Sub-Model

Model Parameter	*Conventional Initial Cost*	*Conventional Annual Cost*	*Green Initial Cost*	*Green Annual Cost*	*GRIPV Green Module Installation Cost*
Constant Value	217,800 USD/Acre	6,534 USD /(Acre-Year)	816,750 USD/Acre	27,225 USD /(Acre-Year)	696,960 USD/Acre
Sources & Comments	(AMS 2016)	(AMS 2016)	This value is the average of the relevant literature data (Table A6).	This value is the average of the relevant literature data (Table A6).	(NYCPR 2013)

Table D30: Standardized Cost Formulas – Economic Sub-Model

Model Parameter	*Conventional Roof Standardized Cost*
Parameter Formula	$\left(\frac{(Cost_{Initial})_{Conv} + (L_{Conv})(Cost_{Annual})_{Conv}}{L_{Conv}}\right)(1\ year)$
Comments	$(Cost_{Initial})_{Conv}$ = Conventional Initial Cost $(Cost_{Annual})_{Conv}$ = Conventional Annual Cost L_{Conv} = Conventional Roof Lifetime (See Table D36) Standardized cost refers to the cost per unit area in any given simulation year, so the formula has been multiplied by "1 year" to reflect this time frame.

Model Parameter	*Green Roof Standardized Cost*
Parameter Formula	$\left(\frac{(Cost_{Initial})_{Green} + (L_{Green})(Cost_{Annual})_{Green}}{L_{Green}}\right)(1\ year)$
Comments	$(Cost_{Initial})_{Green}$ = Green Initial Cost $(Cost_{Annual})_{Green}$ = Green Annual Cost L_{Green} = Green Roof Lifetime (See Table D36) Standardized cost refers to the cost per unit area in any given simulation year, so the formula has been multiplied by "1 year" to reflect this time frame.

Model Parameter	*Solar Roof Standardized Cost*
Parameter Formula	$(LCOE_{Solar})(h_{Sun})(p_{Solar})(1\ year)$
Comments	$LCOE_{Solar}$ = Solar Total LCOE h_{Sun} = Annual Sun Hours p_{Solar} = Solar Power Capacity Per Acre Standardized cost refers to the cost per unit area in any given simulation year, so the formula has been multiplied by "1 year" to reflect this time frame.

Table D31: GRIPV Standardized Cost Formula – Economic Sub-Model

Model Parameter	*GRIPV Direct Standardized Cost*
Parameter Formula	$$(1\ year) * \left(\left(\frac{(Cost_{Initial})_{GG} + (L_{Green})(Cost_{Annual})_{Green}}{L_{Green}}\right) + (SC)(LCOE_{Solar})(h_{Sun})(p_{Solar})\right)$$
Comments	$(Cost_{Initial})_{GG}$ = GRIPV Green Module Installation Cost $(Cost_{Annual})_{Green}$ = Green Annual Cost L_{Green} = Green Roof Lifetime (See Table D36) SC = GRIPV Solar Coverage (See Table D39) $LCOE_{Solar}$ = Solar Total LCOE h_{Sun} = Annual Sun Hours p_{Solar} = Solar Power Capacity Per Acre Standardized cost refers to the cost per unit area in any given simulation year, so the formula has been multiplied by "1 year" to reflect this time frame.

Table D32: Standardized Net Value Formulas – Economic Sub-Model

Model Parameter	*Conventional Roof SNV*	*Green Roof SNV*	*Solar Roof SNV*	*GRIPV Roof Direct SNV*
Parameter Formula	$-gc_{Conv}$	$(os_{Green} + fi_{Green}) - gc_{Green}$	$(os_{Solar} + fi_{Solar}) - gc_{Solar}$	$(os_{GRIPV} + fi_{GRIPV}) - gc_{GRIPV}$
Comments	gc_{Conv} = Conventional Roof Standardized Cost	os_{Green} = Standardized Green Op Savings fi_{Green} = Standardized Green Incentives gc_{Green} = Green Roof Standardized Cost	os_{Solar} = Standardized Solar Op Savings fi_{Solar} = Standardized Solar Incentives gc_{Solar} = Solar Roof Standardized Cost	os_{Green} = Standardized GRIPV Op Savings fi_{Green} = Standardized GRIPV Incentives gc_{GRIPV} = GRIPV Direct Standardized Cost

Figure D13: Economic Sub-Model – Standardized Net Value

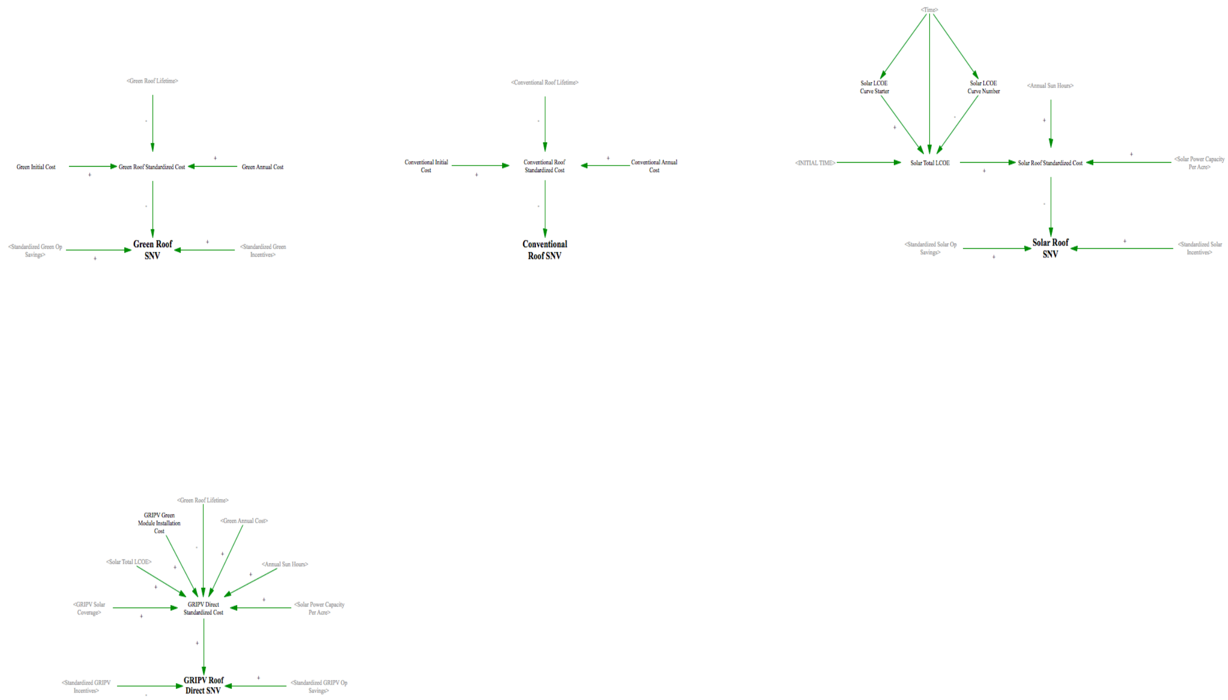


Table D33: Feasibility of Government Support – Economic Sub-Model

Model Parameter	*Feasibility of Government Support*
Parameter Formula	$\dfrac{(GDP)(1 - IF_{Green} - IF_{Solar}) - PS_{Green} - PS_{Solar}}{GDP}$
Comments	IF_{Green} = Green GDP Investment Fraction PS_{Green} = Private Green Subsidies IF_{Solar} = Solar GDP Investment Fraction PS_{Solar} = Private Solar Subsidies "IF" and "PS" are both policy variables (See Tables F2 and F5).

Figure D14: Economic Sub-Model – Feasibility of Government Support

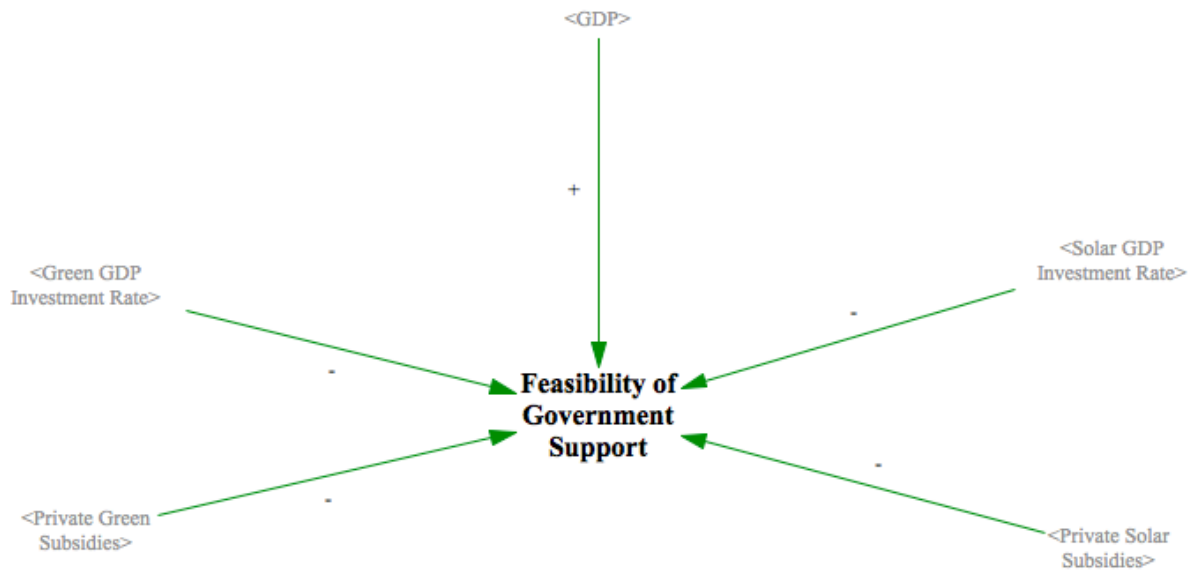


Table D34: Cost Effectiveness Formulas – Economic Sub-Model

Model Parameter	*Green Roof Cost Effectiveness*	*Solar Roof Cost Effectiveness*	*GRIPV Roof Cost Effectiveness*
Parameter Formula	$\frac{SNV_{Green}}{\sum_{l=1}^{4}(SNV_l)}$	$\frac{SNV_{Solar}}{\sum_{l=1}^{4}(SNV_l)}$	$\frac{SNV_{GRIPV}}{\sum_{l=1}^{4}(SNV_l)}$
Comments	SNV_{Green} = Green Roof SNV $\sum_{l=1}^{4}(SNV_l)$ = Sum of All "SNV" Parameters (Table D32) "l" is the set of all conventional and alternative roofing options, indexed on "L".	SNV_{Solar} = Solar Roof SNV $\sum_{l=1}^{4}(SNV_l)$ = Sum of All "SNV" Parameters (Table D32) "l" is the set of all conventional and alternative roofing options, indexed on "L".	SNV_{GRIPV} = GRIPV Roof Direct SNV $\sum_{l=1}^{4}(SNV_l)$ = Sum of All "SNV" Parameters (Table D32) "l" is the set of all conventional and alternative roofing options, indexed on "L".

Figure D15: Economic Sub-Model – Cost-Effectiveness

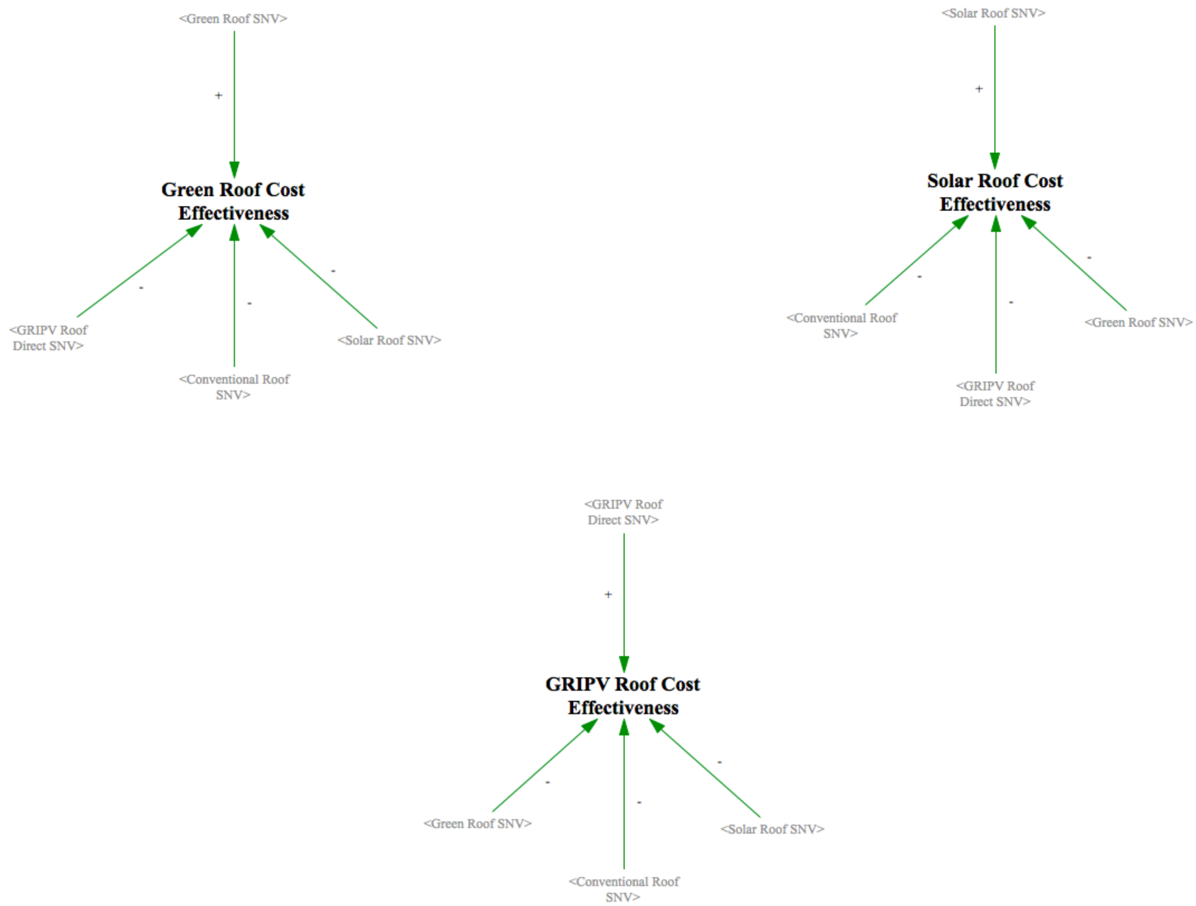


Table D35: Learning Curves – Practical Sub-Model

Time Period	*1985 to 2019*[1]	*2019*[1] *to 2040*
Solar Mounting Weight Per SF (kg/ft^2)	0.1542	$0.6445e^{(-0.24*(Time-2019))}$
Comments	The initial value of this curve was estimated based on available average loading data for roof-mounted solar PV arrays (Diehl 2015), and mounting weight is assumed to decrease to nearly zero by 2040 as BIPV roofing becomes more prevalent from 2019 onward (PR Newswire 2015).	

Time Period	*1985 to 2019*[1]	*2019*[1] *to 2040*
Solar Panel Thickness (ft)	0.031	$0.0305118e^{(-0.0118*(Time-2019))}$
Comments	The initial value of this curve was estimated based on available solar panel layer data for roof-mounted solar PV panels (Wang et al. 2006), and solar panel thickness is assumed to decrease to the standard thickness of the modeled BIPV solar shingle (United Solar Ovonic 2004) by 2040 as BIPV roofing becomes more prevalent from 2019 onward (PR Newswire 2015).	

Time Period	*1985 to 2019*[1]	*2019*[1] *to 2040*
Solar Panel Density (ft)	0.031	$0.0305118e^{(-0.0118*(Time-2019))}$
Comments	The initial value of this curve was estimated based on available solar panel layer data for roof-mounted solar PV panels (Wang et al. 2006), and solar panel thickness is assumed to decrease to the standard thickness of the modeled BIPV solar shingle (United Solar Ovonic 2004) by 2040 as BIPV roofing becomes more prevalent from 2019 onward (PR Newswire 2015).	

[1]2019 was selected as the commercial introduction year for BIPV roofing (see Table D38).

Table D36: Roof Lifetimes – Practical Sub-Model

Model Parameter	*Conventional Roof Lifetime*	*Green Roof Lifetime*	*Solar Roof Lifetime*	*GRIPV Roof Lifetime*
Constant Value	18 years	42 years	25 years	42 years
Sources & Comments	This is the average of the relevant literature data (Table A5).	This is the average of the relevant literature data (Table A5).	(NREL 2016b) The shortest lifetime was used in this study in order to account for the degradation of solar PV energy output over time.	Since green roofing lasts longer on average than solar roofing, GRIPV roofing was assumed to have the same lifetime as green roofing.

Table D37: Contractor Experience Constants – Practical Sub-Model

Model Parameter	*Green Contractor Experience (Initial Value)*	*Solar Contractor Experience (Initial Value)*	*GRIPV Contractor Experience (Initial Value)*
Constant Value	3	7	2.1
Sources & Comments	This value was selected based on applicable market penetration data (Greenroofs.com 2017d).	This value was selected based on applicable market penetration data (Burr et al. 2014).	$\frac{((Exp_{Initial})_{Green})((Exp_{Initial})_{Solar})}{(Exp_{Initial})_{Green} + (Exp_{Initial})_{Solar}}$

Model Parameter	*Green Contractor Training*	*Solar Contractor Training*
Constant Value	0.0012	0.007
Sources & Comments	This value was selected based on applicable market penetration data (Greenroofs.com 2017d).	This value was selected based on applicable market penetration data (Burr et al. 2014).

Table D38: Other Practical Constants – Practical Sub-Model

Model Parameter	*Green Roof Vegetation Load*	*BIPV Intro Year*	*GRIPV Vegetation Cover Growth*	*GRIPV Solar Coverage*
Constant Value	0.95 kg/ft^2	2019	0.056	0.488969
Sources & Comments	(Francis et al. 2014) Since all green roofs in this study were assumed to be extensive, "Low herbaceous" vegetation data was used for the primary data input.	(PR Newswire 2015) This is set as the year when BIPV roofing starts to become more prevalent in the solar roof market (See Table D34).	(Köhler et al. 2007) This value was selected based on long-term increases in plant cover.	This value was selected based on the provided design specifications for the Sun-Root™ System (Optigreen International AG 2017a,b).

Table D39: GRIPV Design Formulas – Practical Sub-Model

Model Parameter	*GRIPV Green Only Fraction*	*GRIPV Contractor Training*	*GRIPV Roof Vegetation Load*
Parameter Formula	$IF\ THEN\ ELSE\begin{pmatrix} 0 \leq SC \leq 1, \\ 1 - SC, \\ NaN \end{pmatrix}$	$\frac{(Tr_{Green})(Tr_{Solar})}{Tr_{Green} + Tr_{Solar}}$	$W_{Veg} * (1 + VCG)$
Comments	SC = GRIPV Solar Coverage "NaN" indicates an undefined data point. The "IF THEN ELSE" function in this formula automatically excludes any data point(s) for which "GRIPV Solar Coverage" and "GRIPV Green Only Fraction" are not both non-negative constants and/or do not add up to 1.	Tr_{Green} = Green Contractor Experience Tr_{Solar} = Solar Contractor Experience	W_{Veg} = Green Roof Vegetation Load VCG = GRIPV Vegetation Cover Growth

Table D40: Roof Load Formulas – Practical Sub-Model

Model Parameter	*Conventional Roof Load Per SF*	*Green Roof Load Per SF*	*Solar Roof Load Per SF*
Parameter Formula	$\rho_{Conv} t_{Conv}$	$\rho_{Green} t_{Green} + W_{Veg}$	$\rho_{Solar} t_{Solar} + W_{Mount}$
Comments	ρ_{Conv} = Conventional Roof Density t_{Conv} = Conventional Roof Thickness	ρ_{Green} = Green Roof Density t_{Green} = Green Roof Thickness W_{Veg} = Green Roof Vegetation Load	ρ_{Solar} = Solar Roof Density t_{Solar} = Solar Roof Thickness W_{Mount} = Solar Mounting Weight Per SF

Model Parameter	*GRIPV Roof Load Per SF*
Parameter Formula	$\rho_{GRIPV} t_{GRIPV} + (SC)(W_{Mount}) + W_{GV}$
Comments	ρ_{GRIPV} = GRIPV Roof Density t_{GRIPV} = GRIPV Roof Thickness SC = GRIPV Solar Coverage W_{Mount} = Solar Mounting Weight Per SF W_{GV} = GRIPV Roof Vegetation Load

Table D41: Contractor Learning Formulas – Practical Sub-Model

Model Parameter	*Green Contractor Learning*	*Solar Contractor Learning*	*GRIPV Contractor Learning*
Parameter Formula	$Exp_{Green} Tr_{Green}$	$Exp_{Solar} Tr_{Solar}$	$Exp_{GRIPV} Tr_{GRIPV}$
Comments	Exp_{Green} = Green Contractor Experience Tr_{Green} = Green Contractor Training This is the sole inflow for "Green Contractor Experience".	Exp_{Solar} = Solar Contractor Experience Tr_{Solar} = Solar Contractor Training This is the sole inflow for "Solar Contractor Experience".	Exp_{GRIPV} = GRIPV Contractor Experience Tr_{GRIPV} = GRIPV Contractor Training This is the sole inflow for "GRIPV Contractor Experience".

Table D42: Practicality Formulas – Practical Sub-Model

Model Parameter	*Market Impact of Green Roof Lifetime*	*Market Impact of Solar Roof Lifetime*	*Market Impact of GRIPV Roof Lifetime*
Parameter Formula	$\frac{L_{Green}}{\sum_{l-1}^{4}(L_l)}$	$\frac{L_{Solar}}{\sum_{l-1}^{4}(L_l)}$	$\frac{L_{Green}}{\sum_{l-1}^{4}(L_l)}$
Comments	L_{Green} = Green Roof Lifetime L = Roof Lifetime "l" is the set of all conventional and alternative roof options, indexed on "L".	L_{Solar} = Solar Roof Lifetime L = Roof Lifetime "l" is the set of all conventional and alternative roof options, indexed on "L".	L_{GRIPV} = GRIPV Roof Lifetime L = Roof Lifetime "l" is the set of all conventional and alternative roof options, indexed on "L".

Model Parameter	*Market Impact of Green Roof Loading*	*Market Impact of Solar Roof Loading*	*Market Impact of GRIPV Roof Lifetime*
Parameter Formula	$\frac{w_{Green}}{\sum_{l-1}^{4}(w_l)}$	$\frac{w_{Solar}}{\sum_{l-1}^{4}(w_l)}$	$\frac{w_{GRIPV}}{\sum_{l-1}^{4}(w_l)}$
Comments	w_{Green} = Green Roof Load Per SF w = Roof Load Per SF "l" is the set of all conventional and alternative roof options, indexed on "L".	w_{Solar} = Solar Roof Load Per SF w = Roof Load Per SF "l" is the set of all conventional and alternative roof options, indexed on "L".	w_{GRIPV} = GRIPV Roof Load Per SF w = Roof Load Per SF "l" is the set of all conventional and alternative roof options, indexed on "L".

Model Parameter	*Green Roof Practicality*	*Solar Roof Practicality*	*GRIPV Roof Practicality*
Parameter Formula	$\frac{(CE_{Green})(MILife_{Green})}{MILoad_{Green}}$	$\frac{(CE_{Solar})(MILife_{Solar})}{MILoad_{Solar}}$	$\frac{(CE_{GRIPV})(MILife_{GRIPV})}{MILoad_{GRIPV}}$
Comments	CE_{Green} = Green Contractor Experience $MILife_{Green}$ = Market Impact of Green Roof Lifetime $MILoad_{Green}$ = Market Impact of Green Roof Loading	CE_{Solar} = Solar Contractor Experience $MILife_{Solar}$ = Market Impact of Solar Roof Lifetime $MILoad_{Solar}$ = Market Impact of Solar Roof Loading	CE_{GRIPV} = GRIPV Contractor Experience $MILife_{GRIPV}$ = Market Impact of GRIPV Roof Lifetime $MILoad_{GRIPV}$ = Market Impact of GRIPV Roof Loading

Figure D16: Practical Sub-Model – Green Roof Practicality

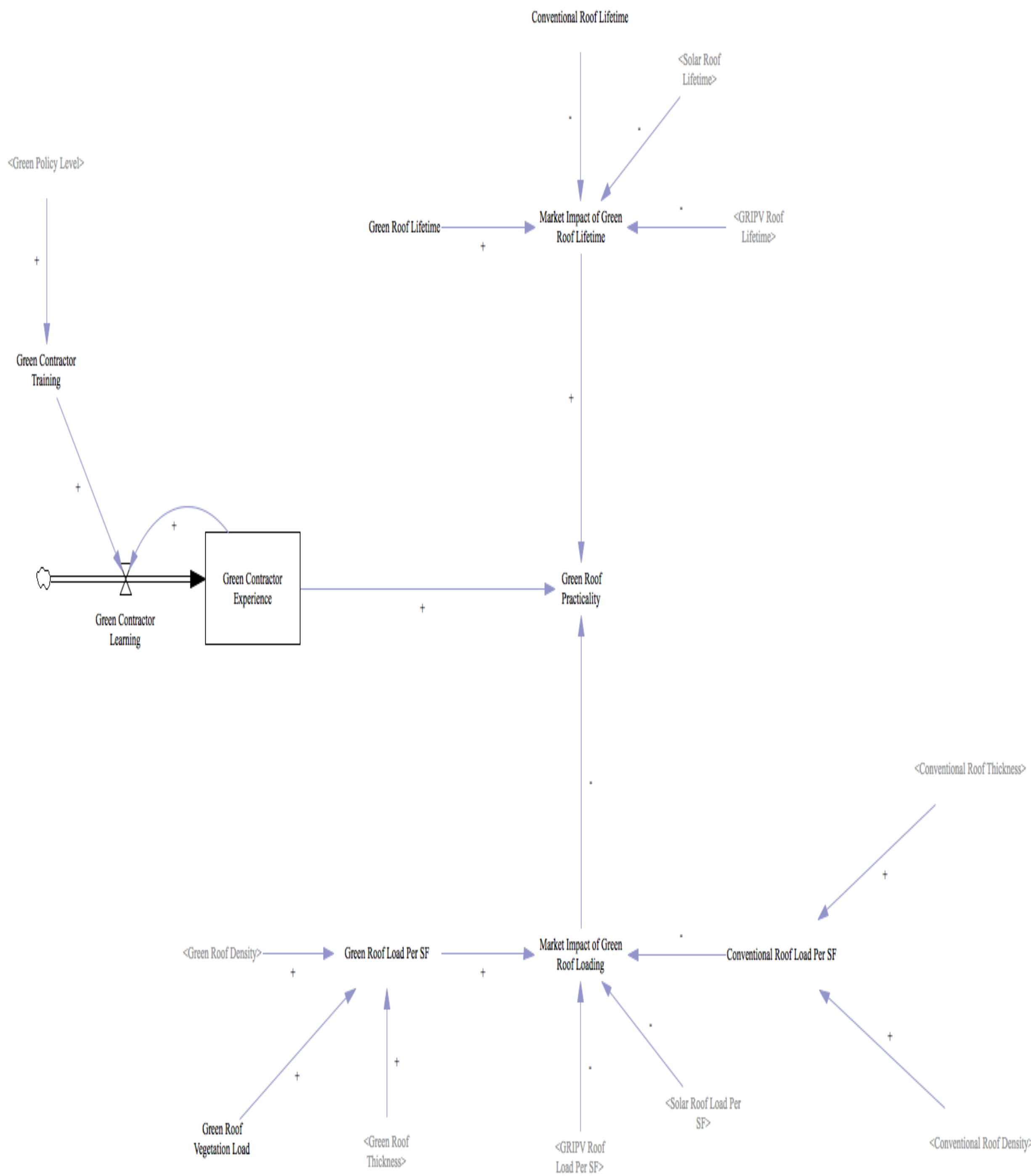


Figure D17: Practical Sub-Model – Solar Roof Practicality

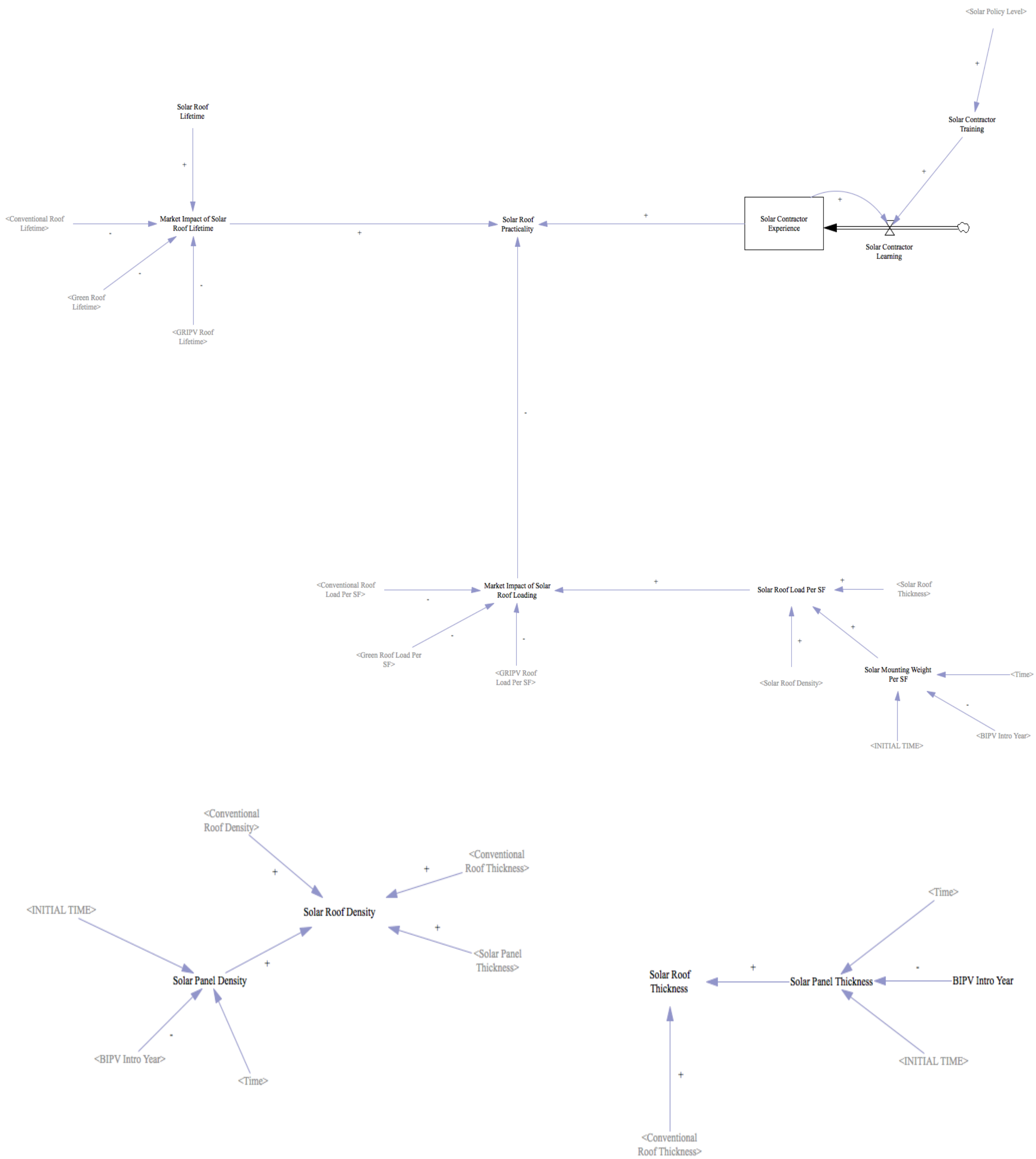


Figure D18: Practical Sub-Model – GRIPV Roof Practicality

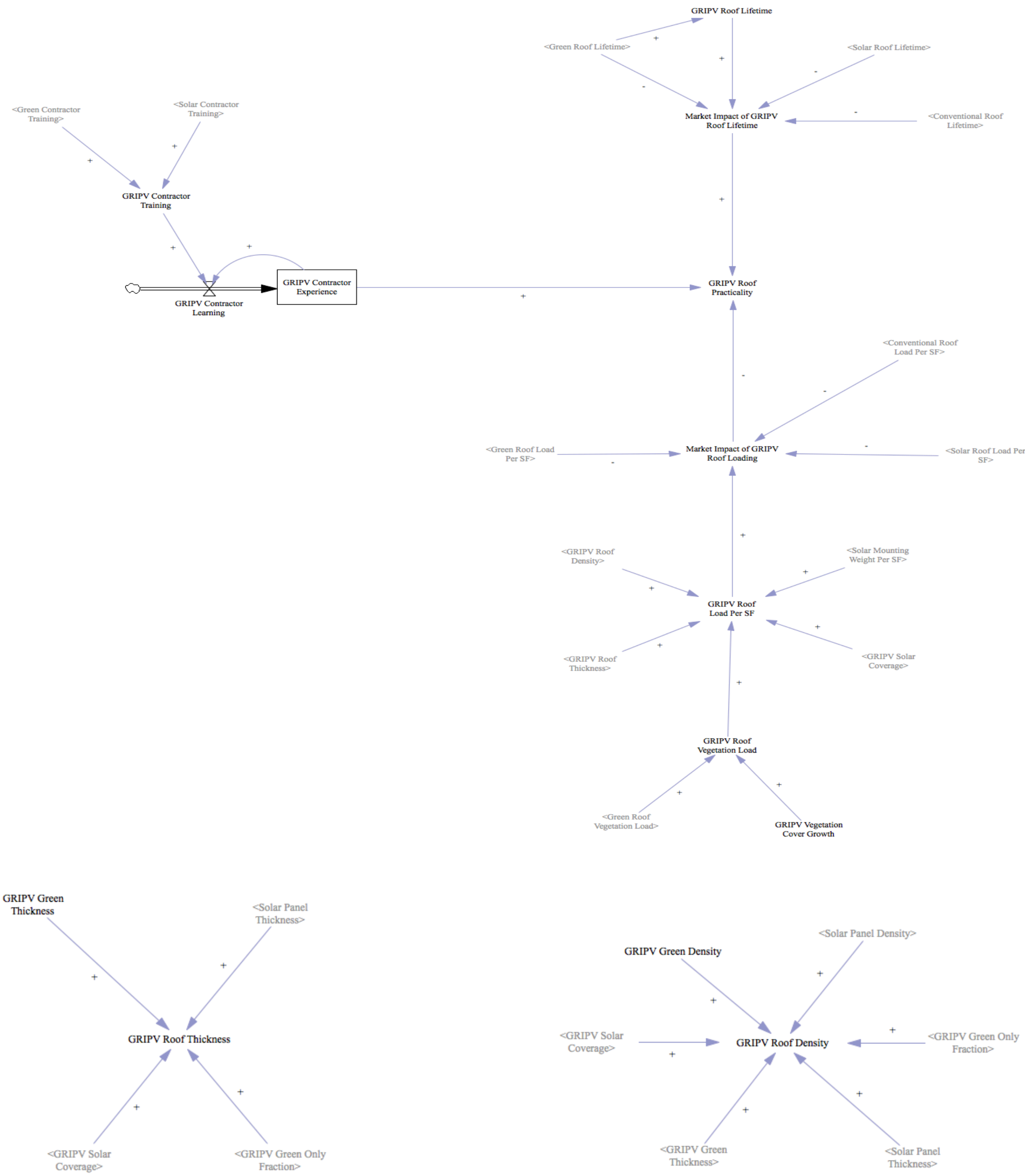


Table D43: Reference Mode Data Sources

Reference Mode	*Green Roof Area*	*Total Runoff*	*Actual Air Temperature Anomaly*
Data Source(s)	(Greenroofs.com 2017d)	(FSU 2016) (Pandit and Gopalakrishnan 1996)	(FSU 2016)

APPENDIX E:
BEHAVIORAL VALIDATION PROCESS RESULTS

The model outputs during the validation period are presented in Figures E1 through E8, with applicable reference modes included for each variable. The resulting graphs appear visually reasonable, and those with reference modes appear to be reasonably close to the reference mode data, but more quantitative/statistical testing is needed to definitively confirm that the model's behavior is valid.

Figure E1: Conventional Roof Area Validation Graph

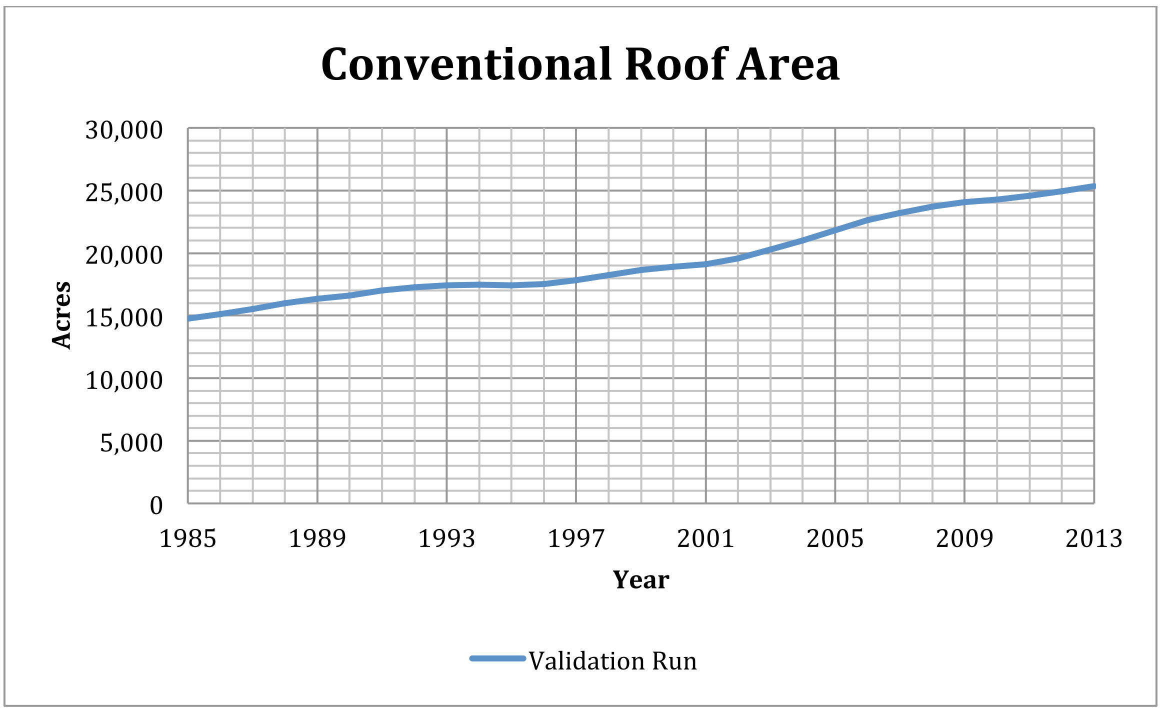


Figure E2: Green Roof Area Validation Graphs

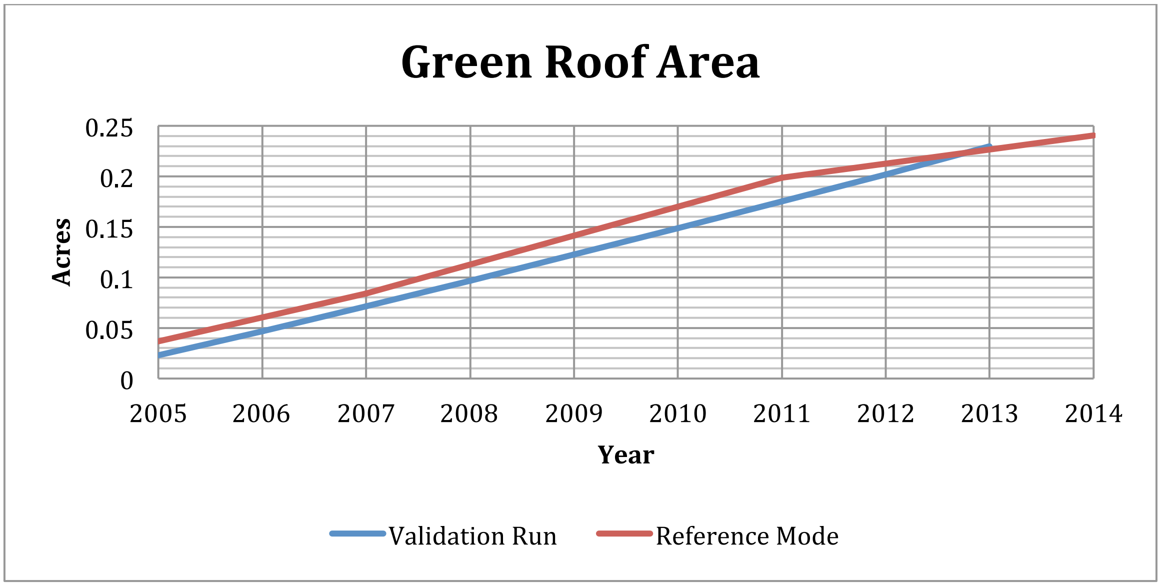


Figure E3: Solar Roof Area Validation Graph

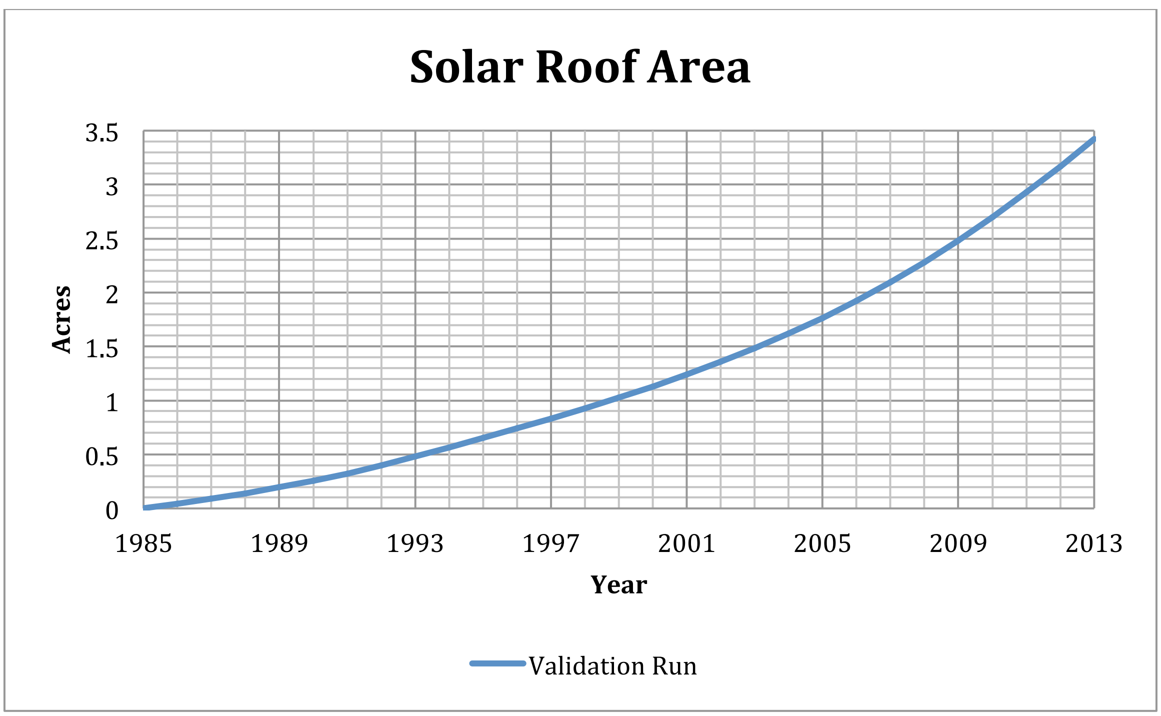


Figure E4: GRIPV Roof Area Validation Graph

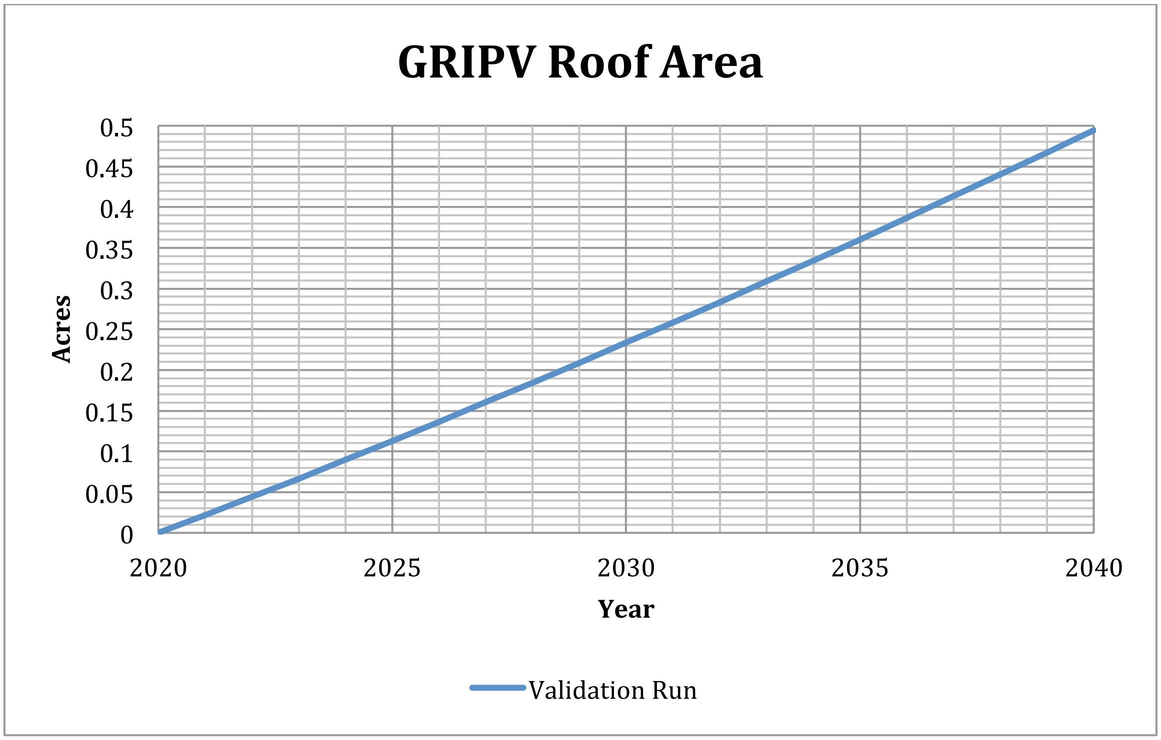


Figure E5: Total Runoff Validation Graphs

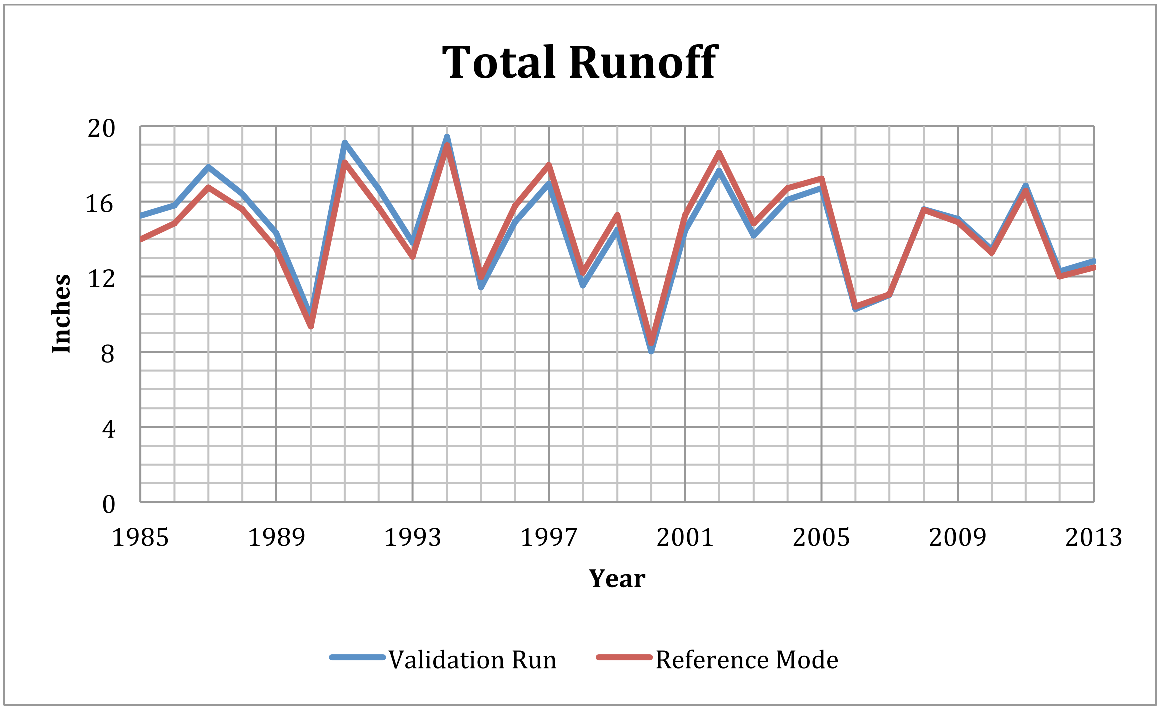


Figure E6: Actual Air Temperature Anomaly Validation Graphs

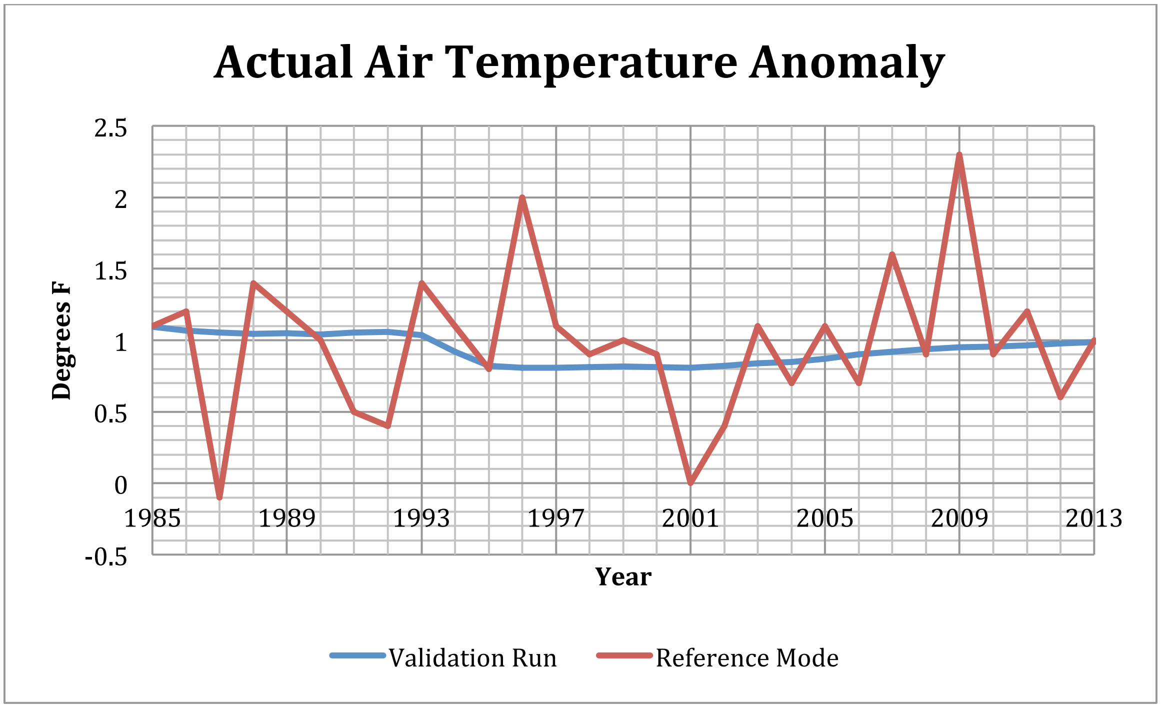


Figure E7: Energy Goal Progress Validation Graph

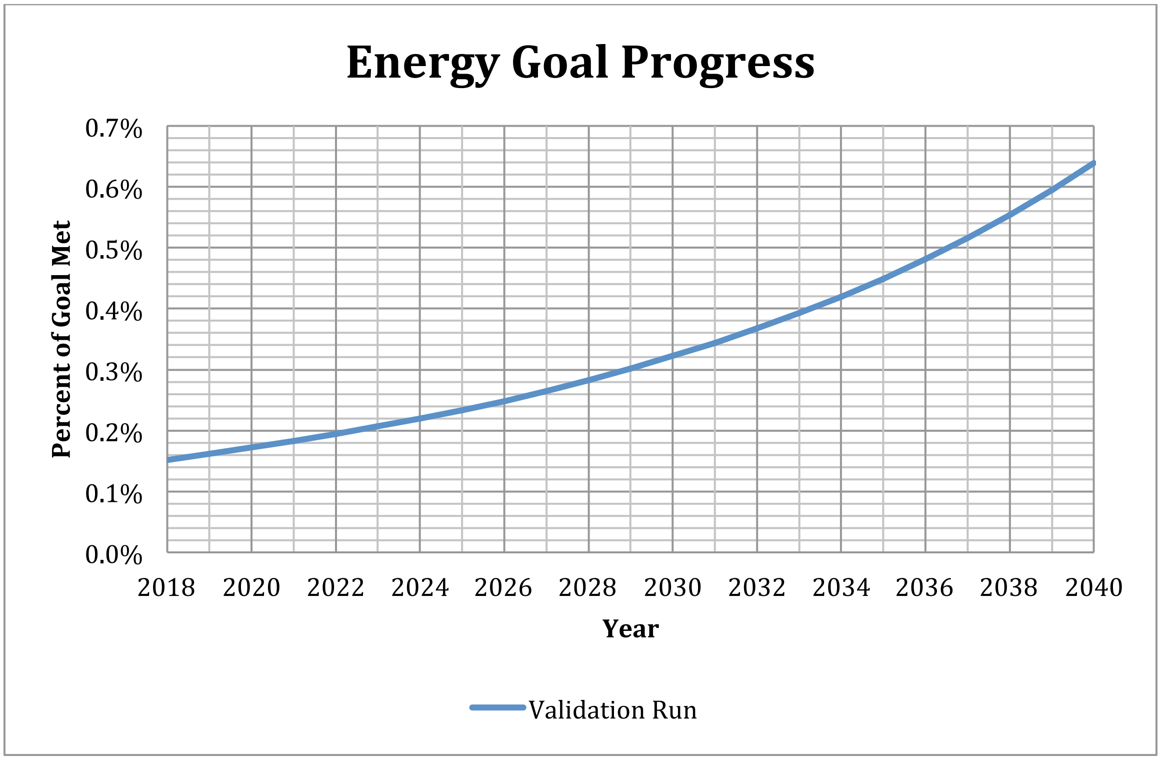
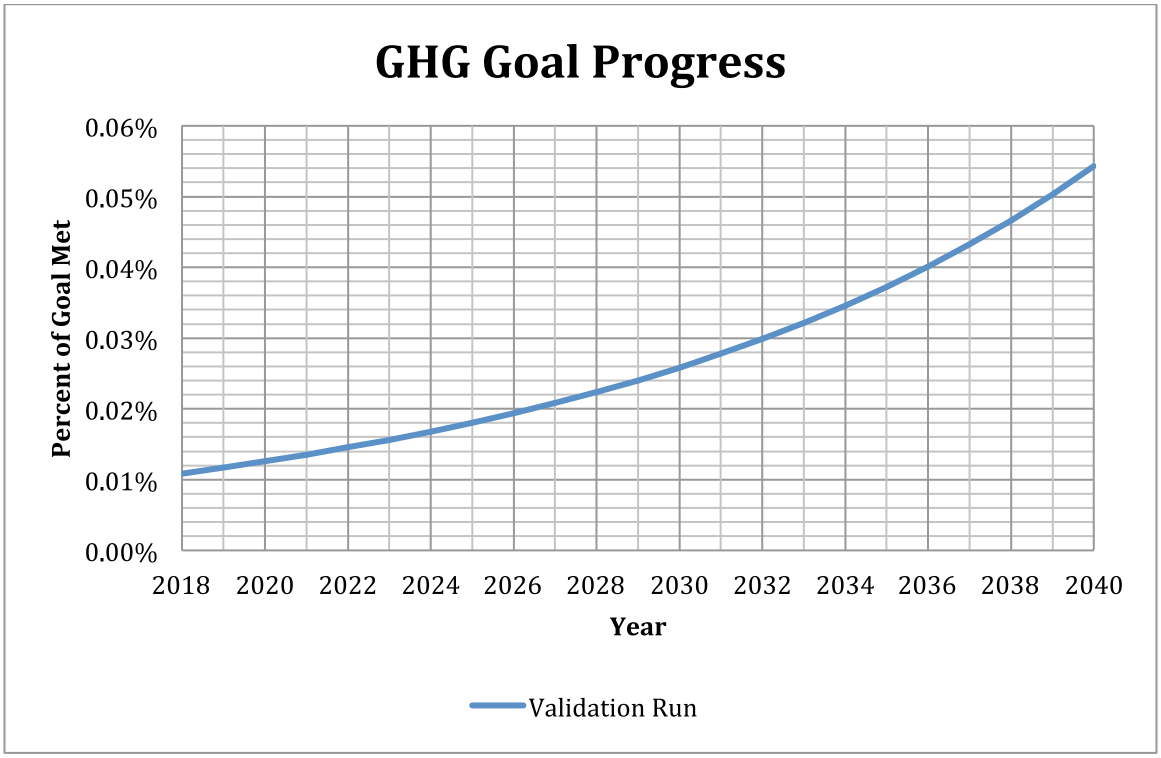


Figure E8: GHG Goal Progress Validation Graph



The three variables with usable reference mode data must be subjected to normality and equal variance tests in order to determine which test (One-Way ANOVA or Kruskal-Wallis) should be used to statistically compare each output with its respective reference mode. The normality test results and equal-variance F-test results are shown in Tables E1 and E2, respectively. To pass each test, the significance value must be greater than or equal to the desired confidence parameter (α) of 0.05.

Table E1: Behavior Reproduction Test – Normality Test Results

Parameter (Data Set)	*Green Roof Area (Model Output)*	*Total Runoff (Model Output)*	*Actual Air Temperature Anomaly (Model Output)*
Kolmogorov-Smirnov Test Statistic	0.22094	0.06783	0.14831
Kolmogorov-Smirnov Significance	NaN (Undefined)	0.98142	0.1056
Shapiro-Wilk Test Statistic	0.92538	0.9759	0.88899
Shapiro-Wilk Significance	0.56754	0.72646	0.00539

Parameter (Data Set)	*Green Roof Area (Reference Mode)*	*Total Runoff (Reference Mode)*	*Actual Air Temperature Anomaly (Reference Mode)*
Kolmogorov-Smirnov Test Statistic	0.10416	0.09929	0.05301
Kolmogorov-Smirnov Significance	0.99564	0.65764	1
Shapiro-Wilk Test Statistic	0.97134	0.97281	0.95065
Shapiro-Wilk Significance	0.90594	0.6379	0.19024

Table E2: Behavior Reproduction Test – Two-Sample Variance F-Test Results

Parameter	*Green Roof Area*	*Total Runoff*	*Actual Air Temperature Anomaly*
F	1.8137	1.05158	25.29204
Critical F	5.41596	2.12992	2.12992
Significance	0.77737	0.89508	0

The model output for "Actual Air Temperature Anomaly" fails the F-test (Table E2) and the Shapiro-Wilk normality test (Table E1), so it must be tested using the Kruskal-Wallis test. On the other hand, the model outputs for "Green Roof Area" and "Total Runoff" pass all normality and equal-variance tests, and can both therefore be tested using the One-Way ANOVA test. These test results are summarized in Tables E3 and E4.

Table E3: Behavior Reproduction Test – One-Way ANOVA Test Results

Parameter	*F Statistic*	*Critical F Value*	*Significance*
Green Roof Area	0.1149	4.84434	0.74101
Total Runoff	0.00853	4.01297	0.92673

Table E4: Behavior Reproduction Test – Kruskal-Wallis Test Results

Parameter	*H Statistic*	*Corrected H Statistic*	*Significance*
Actual Air Temperature Anomaly	0.88521	0.88632	0.34678

All three parameters pass their respective statistical comparison tests, meaning that their model outputs are all statistically similar to their respective reference modes and are therefore considered to be behaviorally valid.

Next, model parameters without available reference modes must be subjected to a behavior reasonableness test instead. To this end, it is important to consider the past and current contexts associated with each variable in order to determine whether or not the model output is reasonable given the specific circumstances that may influence the model output in this regard:

- *Conventional Roof Area:* The market share of conventional roofs in Orlando's roofing industry (Figure E1) far exceeds those of green and solar roofing combined (Figures E2 and E3), which is consistent with the historically marginal market shares of alternative roofing.
- *Solar Roof Area:* Although no historical data trends are available for solar PV market penetration in Orlando, it is known that Orlando had approximately 2 MW of solar PV installed capacity as of 2013 (Burr et al. 2014). Based on this statistic and the averaged value of "Solar Power Capacity Per Acre" (Table D18), the estimated 2013 solar roof area for purposes of this study was 3.26 acres. The 2013 output value of "Solar Roof Area" was 3.425 acres: a difference of approximately +5%. Since most solar PV roofing projects are installed on a small-scale basis that might not be evident on a MW scale, some degree of error was deemed acceptable in this regard, so this value was considered to be reasonably accurate.
- *GRIPV Roof Area:* No historical data was available for "GRIPV Roof Area" but, as predicted, GRIPV roof market penetration increased at a slower rate than either green or solar roofing individually, which is reasonable in light of the fact that GRIPV roofing, if/when it is introduced into Orlando's alternative roofing market,

would be the newest roofing alternative and would therefore need more time to reach the same level of market maturity.

- *Energy Target/Goal Progress:* The contribution of Orlando's alternative roofing market to energy savings, even on a per-capita basis, is understandably small given the currently marginal alternative roofing market shares as previously noted. For example, based on the 2013 solar PV installed capacity previously noted, the solar PV market in Orlando would generate 14.4 kWh/capita under ideal conditions (assuming 100% efficiency), which is far less than the 12,003 kWh/capita on which the 2040 energy savings target and goal are based (Green Works Orlando 2016). Therefore, the model outputs for "Energy Target Progress" and "Energy Goal Progress" can be considered reasonable despite being very small, given the clear limitations on possible energy savings from the alternative roofing market.
- *GHG Target/Goal Progress:* The contribution of Orlando's alternative roofing market to GHG emission savings is even smaller than its contribution to per-capita energy savings, but this is understandable because, in addition to not being evaluated on a per-capita basis, "GHG Target Progress" and "GHG Goal Progress" are both also very limited due to the currently marginal market penetration trends and possible energy savings of the alternative roofing industry in Orlando, while the only other GHG reduction mechanism being taken into consideration (green/GRIPV roof carbon sequestration) is also very limited in its effectiveness due to marginal green roof market shares and the fact that extensive

green roofs (which were the modeled green roof type for purposes of this study) cannot support as much vegetation as other green roof types. Therefore, the model output for "GHG Target Progress" and "GHG Goal Progress" can also be considered reasonable despite also being very small.

Although the model outputs of all five of these variables can therefore be considered qualitatively reasonable, it is also important to evaluate their reasonableness on a more qualitative basis. In this study, this is done by generating box plots for each variable in order to check for outliers; these outliers, which lie beyond the interquartile or overall ranges of the data set to an unusual degree, would indicate that the corresponding data points are abnormal, which in this test would mean that at least some of the output data is statistically unreasonable. The box plots for the above-cited variables are presented in Figures E9 through E13.

Figure E9: Conventional Roof Area Box Plot

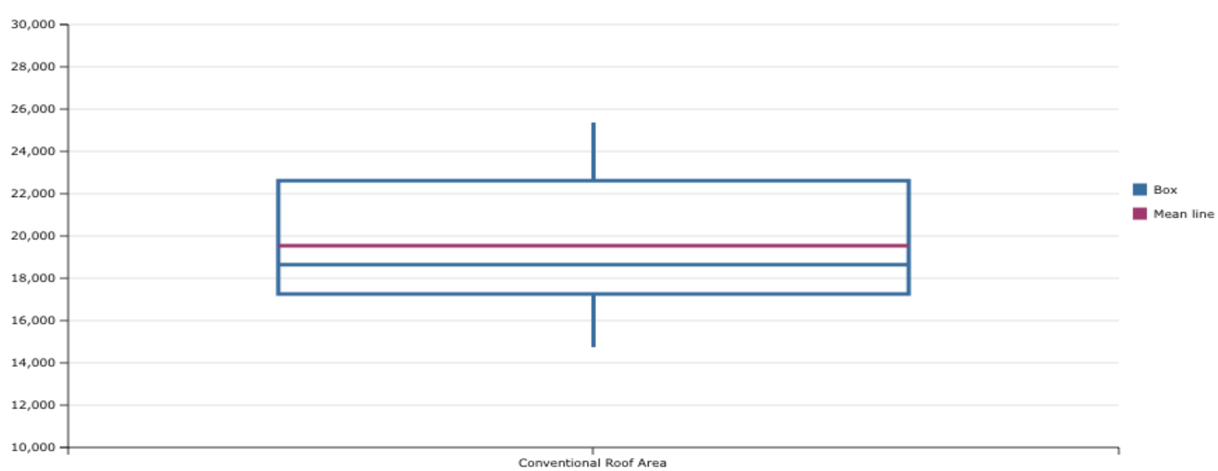


Figure E10: Solar Roof Area Box Plot

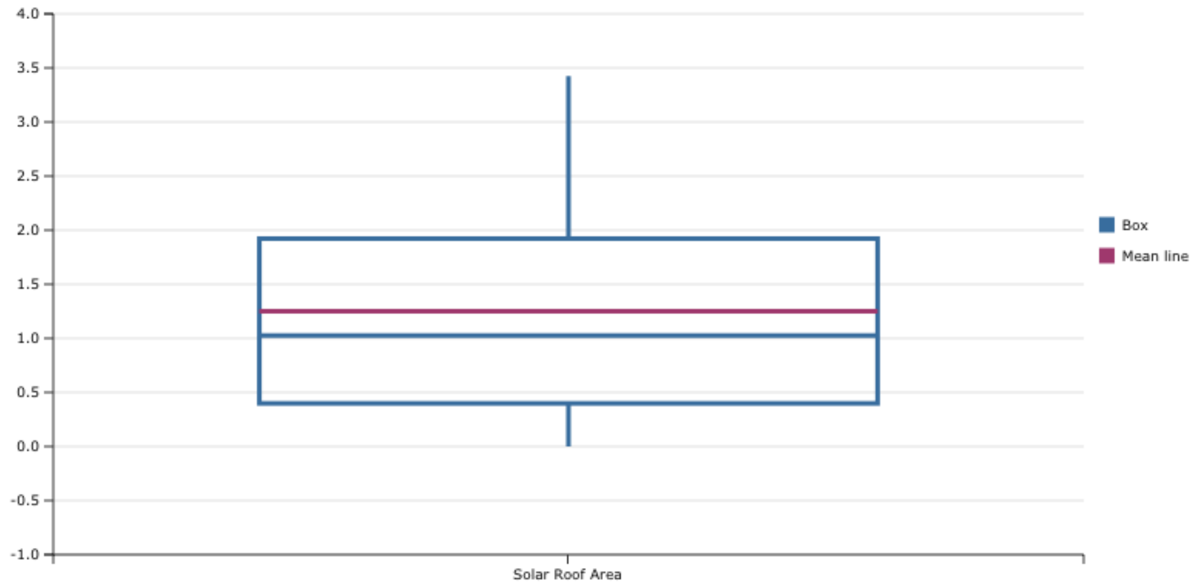


Figure E11: GRIPV Roof Area Box Plot

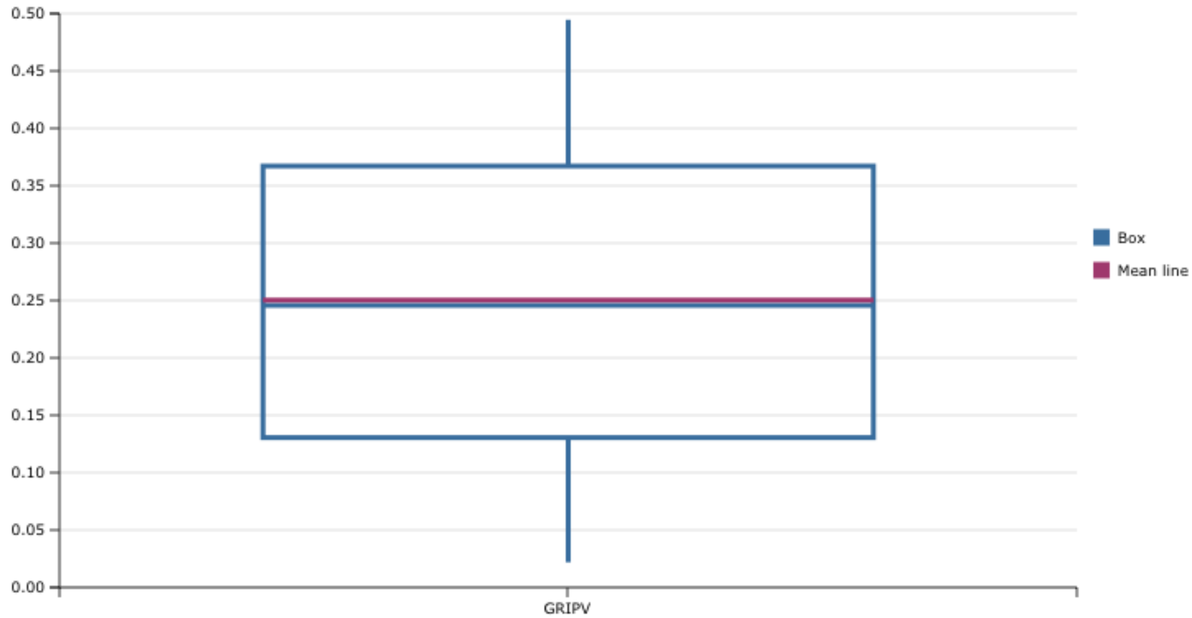


Figure E12: Energy Target/Goal Progress Box Plots

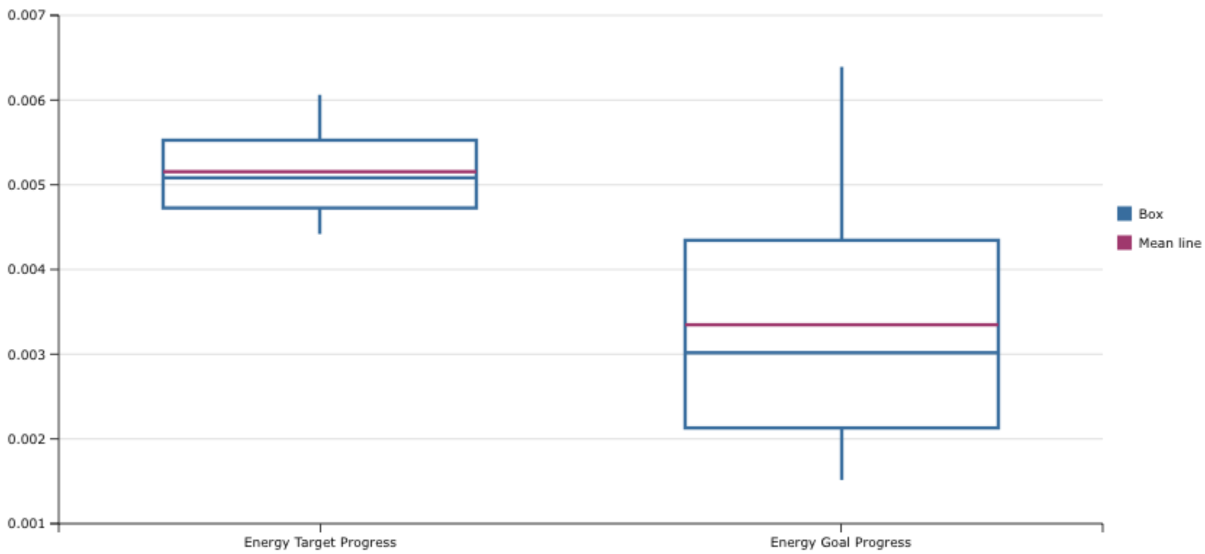
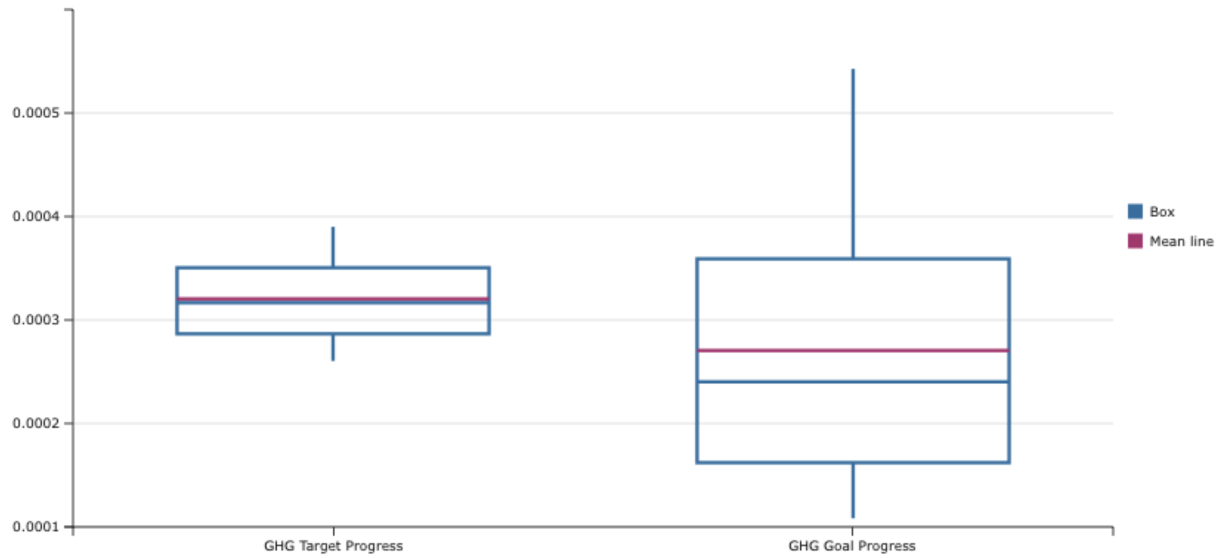


Figure E13: GHG Target/Goal Progress Box Plots



No outliers were evident in any of the above graphs, meaning that all of the model output data for these variables is statistically reasonable.

APPENDIX F:
POLICY ANALYSIS VARIABLE FORMULATION

Table F1: Policy Level Parameters

Model Parameter	*Green Policy Level*	*Green Policy Level*	*GRIPV Market Switch*
Possible Values	$0 * (Policy\ Switch)$ $1 * (Policy\ Switch)$ $2 * (Policy\ Switch)$	$0 * (Policy\ Switch)$ $1 * (Policy\ Switch)$ $2 * (Policy\ Switch)$	0 1
Comments	Policy Level 0 = BAU Scenarios Policy Level 1 = "Green1" Scenarios Policy Level 2 = "Green2" Scenarios	Policy Level 0 = BAU Scenarios Policy Level 1 = "Solar1" Scenarios Policy Level 2 = "Solar2" Scenarios	Policy Level 0 = BAU Scenarios Policy Level 1 = "GRIPV" Scenarios

Table F2: Policy Switches

Model Parameter	*Policy Switch*	*GRIPV Switch*
Formula/Value	$STEP(1,2017)$	$(GRIPV\ Market\ Switch) * \left(STEP\left((1 + GPL + SPL), GIY\right)\right)$
Comments	The "STEP" function in this formula activates all policy multipliers in the simulation year 2017.	GPL = Green Policy Level SPL = Solar Policy Level GIY = GRIPV Intro Year (See Table F3)

Table F3: Other External Policy Constants

Model Parameter	*GRIPV Intro Year*	*Subsidy Increment*
Formula/Value	2020	$1x10^6$ USD
Comments	This was the selected year for the introduction of GRIPV roofing in the "GRIPV" policy scenarios.	This is the increment at which "Private Green Subsidies" or "Private Solar Subsidies" will increase as their respective policy levels increase.

Figure F1: Policy & GRIPV Control Panels

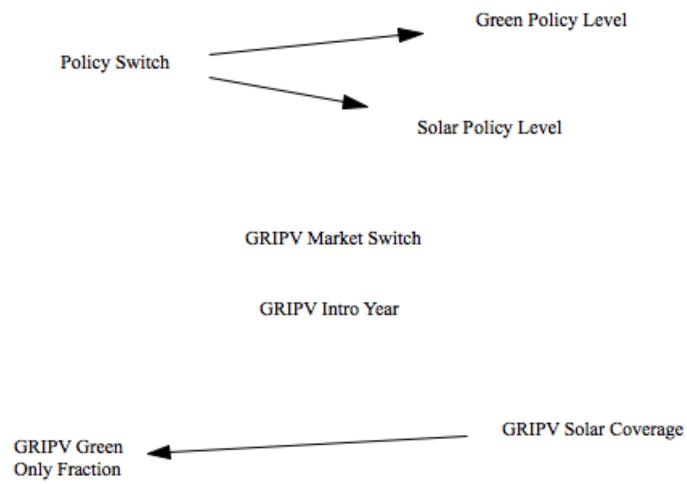


Table F4: "Advert Effect" Parameters with Policy Levels

Model Parameter	*Green Advert Effect*	*Solar Advert Effect*
Formula	$(1.0725\times10^{-6}) * (Green\ Roof\ Market\ Switch) * (1 + Green\ Policy\ Level)$	$(2.691\times10^{-6}) * (1 + Solar\ Policy\ Level)$
Comments	The variable "Green Roof Market Switch" is used to start green roof market penetration in the year 2004.	

Model Parameter	*GRIPV Advert Effect*
Formula	$(GRIPV\ Switch) * \left(\frac{(Green\ Advert\ Effect) * (Solar\ Advert\ Effect)}{(Green\ Advert\ Effect) + (Solar\ Advert\ Effect)}\right)$
Comments	The effectiveness of GRIPV advertising is assumed to be proportional to those of green and solar advertising individually.

Table F5: "GDP Investment Rate" Lookup Inputs at Different Policy Levels

Policy Level	*Green GDP Investment Rate*	*Solar GDP Investment Rate*
0	0	0
1	0.103	0.103
2	0.207	0.207

Table F6: "Private Subsidies" Parameters with Policy Levels

Model Parameter	*Private Green Subsidies*	*Private Solar Subsidies*
Formula	$(Subsidy\ Increment) * (Green\ Policy\ Level)$	$(Subsidy\ Increment) * (Solar\ Policy\ Level)$
Comments		

Table F7: "Contractor Training" Parameters with Policy Levels

Model Parameter	*Green Contractor Training*	*Solar Contractor Training*
Formula	$0.0012 * (1 + Green\ Policy\ Level)$	$0.007 * (1 + Solar\ Policy\ Level)$
Comments	The coefficient of this formula is the original (BAU) value of this parameter from the model formulation (See Table D37).	The coefficient of this formula is the original (BAU) value of this parameter from the model formulation (See Table D37).

APPENDIX G: UNCERTAINTY ANALYSIS PROBABILITY DISTRIBUTIONS

Table G1: Uniform Probability Distributions

Model Parameter	*Minimum Value*	*Maximum Value*
Conventional Initial Cost	174,240 USD/Acre	261,360 USD/Acre
Conventional Annual Cost	2,178 USD/(Acre-year)	10,890 USD/(Acre-year)
Conventional Roof Thickness	0.73 ft	1.25 ft
Conventional Roof Density	26.93 kg/ft^3	46.08 kg/ft^3
Conventional Roof Specific Heat	4.57x10^{-4} kWh/(kg-^{0}F)	4.61x10^{-4} kWh/(kg-^{0}F)
Undeveloped Soil Density	21.52 kg/ft^3	39.64 kg/ft^3
Undeveloped Soil Specific Heat	4.44x10^{-4} kWh/(kg-^{0}F)	6.26x10^{-4} kWh/(kg-^{0}F)
GRIPV Green Thickness	1.17 ft	1.2549 ft
GRIPV Green Density	37.26 kg/ft^3	42.92 kg/ft^3
GRIPV Green Specific Heat	4.44x10^{-4} kWh/(kg-^{0}F)	5.03x10^{-4} kWh/(kg-^{0}F)
Green Roof Annual Retention/ET Efficiency	0.33	0.95
Solar Panel Albedo	0.15	0.178
Conventional Roof Albedo	0.066	0.35
Solar Power Capacity Per Acre	534.29 kW/Acre	692.25 kW/Acre
Solar Cooling Load Reduction Per Acre	12.83 kWh/Acre	13.05 kWh/Acre

Table G2: Triangular Probability Distributions

Model Parameter	*Minimum Value*	*Most Likely Value*	*Maximum Value*
Plant Albedo	0.2	0.303	0.85
Green Cooling Load Reduction Per Acre	1.33 kWh/Acre	3.97 kWh/Acre	8.82 kWh/Acre
Green Roof Lifetime	25 years	42 years	60 years
Solar Roof Lifetime	25 years	25 years	40 years
Conventional Roof Lifetime	8 years	18 years	19 years
GRIPV Solar Coverage	0	0.488969	1
GRIPV Solar Energy Improvement	0.01	0.0373	0.1
Green Roof Thickness	1.28 ft	1.56 ft	1.78 ft
Green Roof Density	35.09 kg/ft^3	39.83 kg/ft^3	42.74 kg/ft^3
Green Roof Specific Heat	4.45x10^{-4} kWh/(kg-^{0}F)	4.69x10^{-4} kWh/(kg-^{0}F)	5.13x10^{-4} kWh/(kg-^{0}F)
Green Initial Cost	217,800 USD/Acre	816,750 USD/Acre	1,089,000 USD/Acre
Green Annual Cost	8,712 USD/(Acre-year)	27,225 USD/(Acre-year)	65,340 USD/(Acre-year)

APPENDIX H:
DETAILED CASE STUDY FORMULATION

The model formulation and uncertainty distributions are the same as in the original model (Appendix D and Appendix G, respectively) except as summarized in the figures and tables below. Updated CLD figures and conceptualizations of these model extensions (excluding all variables whose formulations from previous steps are left unchanged) are also included.

Table H1: Roofing Bylaw Variables for Each Alternative

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Bylaw Requirements • Extra Bylaw Adoption	• Alternative Adoption via Bylaws • Bylaw Criteria	• Coverage Requirements for Individual Roofs

Table H2: Roofing Bylaw Parameters for Each Alternative[1]

Parameter Information	*Type*	*Units*	*Description*
Alternative Adoption via Bylaws	Exogenous	Acres/Year	Total Annual Installation of Alternative Roof Type "i" due to Applicable Roofing Bylaws
Bylaw Criteria	Endogenous	DMNL[2]	Fraction of New Urban Development Targeted Under the Specified Bylaw(s)
Bylaw Requirements	Exogenous	DMNL[2]	Minimum Fraction of Targeted New Development that Requires Alternative Roofing Under the Specified Bylaw(s)
Extra Bylaw Adoption	Endogenous	DMNL[2]	Multiplier Representing the Willingness of Roof Owners to Exceed the Minimum Requirements of the Specified Bylaw(s)

[1]These parameters all apply to green, solar, and GRIPV roofing.
[2]Dimensionless

Figure H1: Main Diffusion CLD for Each Roofing Alternative with Case Study Extensions

Table H3: Case Study Constants

Model Parameter	*Case Study Green Incentives Per Acre*	*Case Study Solar Incentives Per kWh*	*Large Dev Fraction*
Possible Values	0 USD/Acre 390,083.13 USD/Acre	0 USD/kWh 0.09 USD/kWh	0.32
Sources & Comments	(Plant Connection, Inc. 2017) This value was based on all incentives offered per unit area. This value is set to zero if this incentive is not being offered.	(DOE 2017) This value was based primarily on incentives available to Central Florida. This value is set to zero if this incentive is not being offered.	(EIA 2016c) This value is based on the fraction of newer buildings (built between 2008 and 2012) with total floor areas of 100,000 ft^2 or more.

Table H4: Case Study Roofing Bylaw Switches

Model Parameter	*Green Bylaw Switch*	*Solar Bylaw Switch*	*GRIPV Bylaw Switch*
Possible Values	0 1	0 1	0 1
Comments	0 = No Bylaw in Effect 1 = Bylaw in Effect	0 = No Bylaw in Effect 1 = Bylaw in Effect	0 = No Bylaw in Effect 1 = Bylaw in Effect

Table H5: Case Study Roofing Bylaw Formulas – Main Diffusion Model

Model Parameter	*Bylaw Distributor*
Parameter Formula	$\sum_{i=1}^{3} (Bylaw\ Switch)_i$
Comments	"i" is the set of all alternative roofing options, indexed on "I". This parameter is used to allocate equal fractions of non-residential construction to each alternative roofing option for consideration for bylaw adoption, thus ensuring that the total bylaw adoption rate never exceeds the total amount of new roofing construction in each year.

Model Parameter	*Green QAR*
Parameter Formula	$\left(\frac{NRC}{1+NRC}\right) * \left(RANDOM\ UNIFORM(0, (Large\ Dev\ Fraction), 123)\right)$
Comments	QAR = Qualifying Area Randomizer NRC = Non-Residential Function The "RANDOM UNIFORM" function in this formula simulates a randomly selected multiplier between 0 and "Large Dev Fraction" to select the fraction of newly constructed non-residential roofing that will be adopted as green roofing.

Model Parameter	*Solar QAR*
Parameter Formula	$\left(\frac{NRC}{1+NRC}\right) * \left(RANDOM\ UNIFORM(0, (Large\ Dev\ Fraction), 234)\right)$
Comments	QAR = Qualifying Area Randomizer NRC = Non-Residential Function The "RANDOM UNIFORM" function in this formula simulates a randomly selected multiplier between 0 and "Large Dev Fraction" to select the fraction of newly constructed non-residential roofing that will be adopted as green roofing.

Model Parameter	*GRIPV QAR*
Parameter Formula	$\left(\frac{NRC}{1+NRC}\right) * \left(RANDOM\ UNIFORM(0, (Large\ Dev\ Fraction), 345)\right)$
Comments	QAR = Qualifying Area Randomizer NRC = Non-Residential Function The "RANDOM UNIFORM" function in this formula simulates a randomly selected multiplier between 0 and "Large Dev Fraction" to select the fraction of newly constructed non-residential roofing that will be adopted as green roofing.

Table H6: New Adoption Rates – Main Diffusion Model

Model Parameter	*(Case Study Bylaw Adoption)$_i$*
Parameter Formula	$(NC) * (QAR_i) * (PSwitch) * \left(IF\ THEN\ ELSE \left(\begin{matrix} BD = 0, \\ 0, \\ \left(\frac{(Bylaw\ Switch)_i}{BD} \right) \end{matrix} \right) \right)$
Comments	"i" is the set of all alternative roofing options, indexed on "I". NC = New Roofing Construction QAR = Qualifying Area Randomizer (See Table H3) PSwitch = Policy Switch BD = Bylaw Distributor The "IF THEN ELSE" function in this formula prevents errors from dividing by zero by automatically setting this parameter to zero if "Bylaw Distributor" is zero, since no bylaws would be in effect in such a case.

Model Parameter	*(Adoption Rate)$_i$*
Parameter Formula	$(Advert\ Adoption)_i + (WOM\ Adoption)_i + (Bylaw\ Adoption)_i$
Comments	"i" is the set of all alternative roofing options, indexed on "I". "Bylaw Adoption" refers to the case study bylaw adoption parameters ("Case Study Green/Solar/GRIPV Bylaw Adoption").

Figure H2: Main Diffusion Model with Case Study Parameters

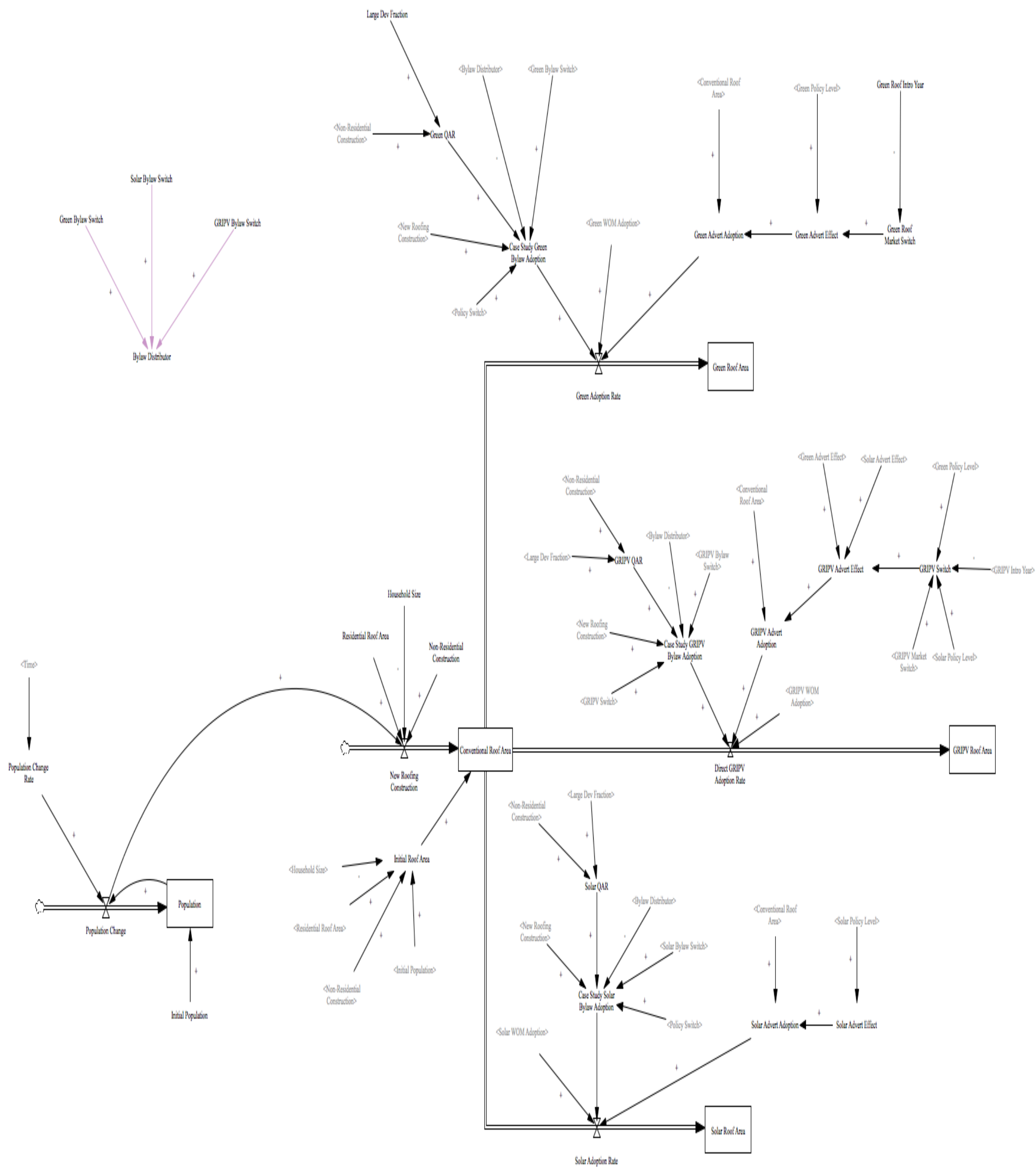


Table H7: Unit-Based Financial Incentive Variables

Variable Category	*Exogenous*	*Endogenous*	*Excluded*
Variables	• Green Incentives Per Acre • Solar Incentives Per kWh	• Green Unit-Based Incentives • Solar Unit-Based Incentives	• GRIPV-Specific Financial Incentives • GRIPV Energy Efficiency Gains As They Apply to Financial Incentives

Table H8: Unit-Based Financial Incentive Parameters

Parameter Information	*Type*	*Units*	*Description*
Green Incentives Per Acre	Exogenous	USD/Acre	Subsidies Offered Per Unit Area of Green Roofing
Green Unit-Based Incentives	Endogenous	USD/Year	Total Yearly Unit-Based Financial Incentives for Green Roofing Installations (Including Replacement & New Adoption)
Solar Incentives Per Acre	Exogenous	USD/kWh	Subsidies Offered Per Unit of Electricity Generation from Solar PV Systems
Solar Unit-Based Incentives	Endogenous	USD/Year	Total Yearly Unit-Based Financial Incentives for Solar Roofing Installations (Including Replacement & New Adoption)

Figure H3: Financial Incentive CLD with Case Study Extensions

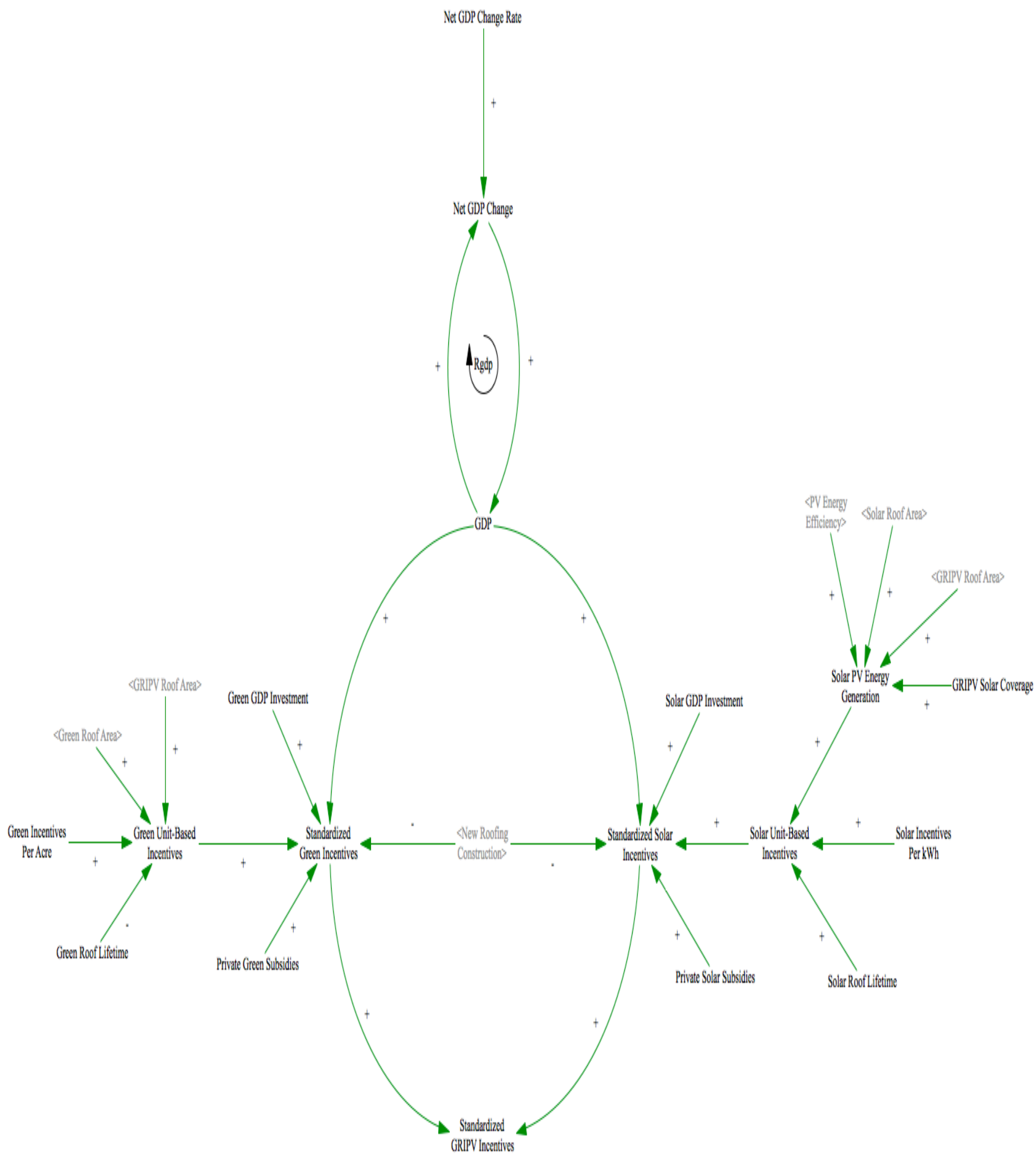


Figure H4: Economic Feasibility Sub-Model with Case Study Extensions

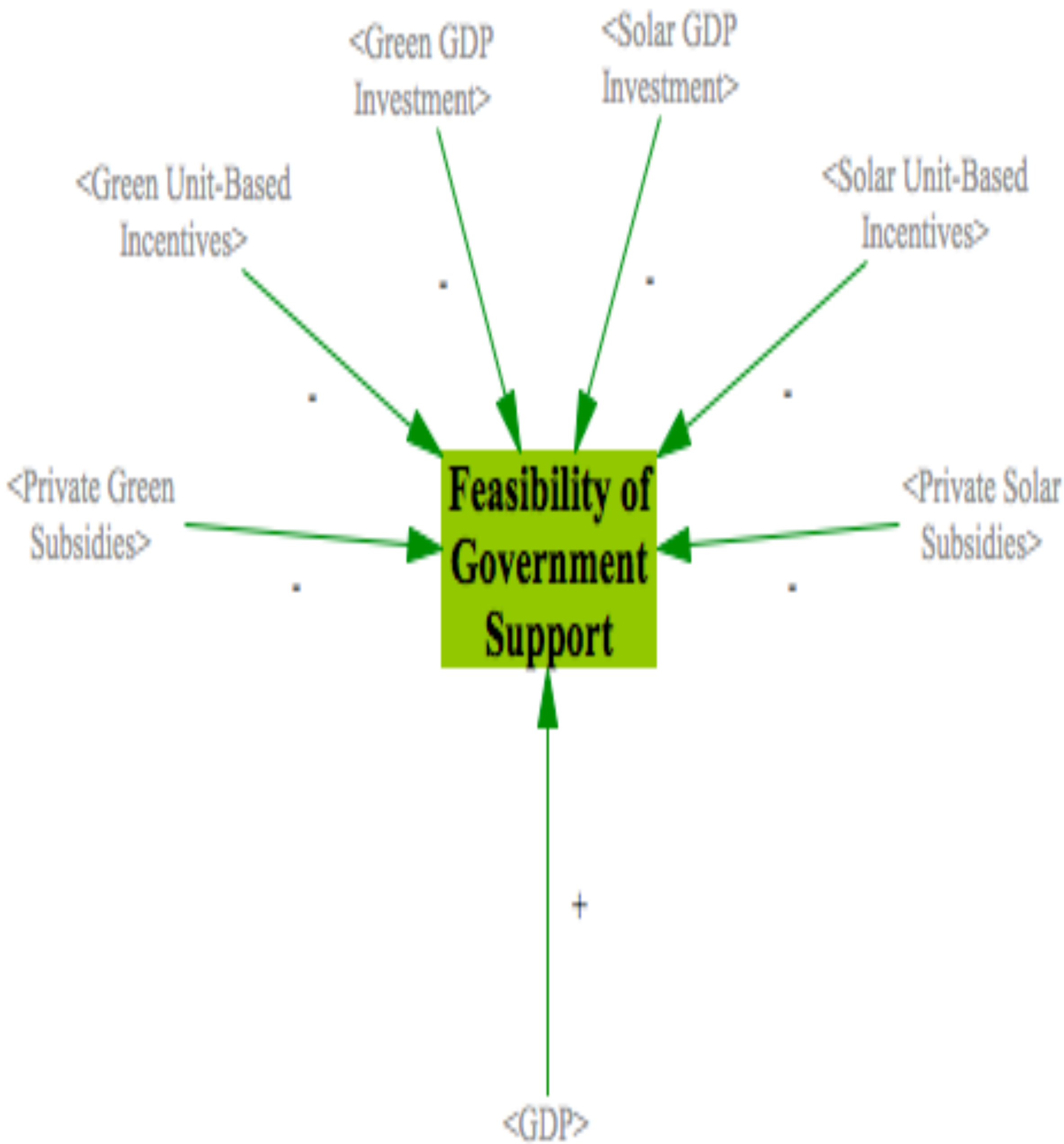


Table H9: Case Study Financial Incentive Formulas – Economic Sub-Model

Model Parameter	*Case Study Green Incentives*	*Case Study Solar Incentives*
Parameter Formula	$(PSwitch) * (csi_{Green}) * \left(\frac{A_{Green} + A_{GRIPV}}{L_{Green}}\right)$	$(PSwitch) * (csi_{Solar}) * (p_{Solar}) * (h_{Sun}) * (\eta_{Solar}) * \left(\frac{A_{Solar} + (A_{GRIPV})(SC)}{L_{Solar}}\right)$
Comments	PSwitch = Policy Switch csi_{Green} = Case Study Green Incentives Per Acre A_{Green} = Green Roof Area A_{GRIPV} = GRIPV Roof Area L_{Green} = Green Roof Lifetime	PSwitch = Policy Switch csi_{Solar} = Case Study Solar Incentives Per kWh p_{Solar} = Solar Power Capacity Per Acre h_{Sun} = Annual Sun Hours η_{Solar} = Solar PV Commercial Efficiency A_{Solar} = Solar Roof Area A_{GRIPV} = GRIPV Roof Area SC = GRIPV Solar Coverage L_{Solar} = Solar Roof Lifetime GRIPV energy efficiency gains are assumed to be negligible for incentive calculation purposes.

Table H10: New Financial Incentive Formulas – Economic Sub-Model

Model Parameter	*Standardized Green Incentives*	*Standardized Solar Incentives*
Parameter Formula	$\frac{(GDP)(IF_{Green}) + PS_{Green} + CSI_{Green}}{NC}$	$\frac{(GDP)(IF_{Solar}) + PS_{Solar} + CSI_{Solar}}{NC}$
Comments	IF_{Green} = Green GDP Investment Fraction PS_{Green} = Private Green Subsidies CSI_{Green} = Case Study Green Incentives NC = New Roofing Construction "IF_{Green}" and "PS_{Green}" will both be set to zero in this case study, since only the case study incentives will be included.	IF_{Solar} = Solar GDP Investment Fraction PS_{Solar} = Private Solar Subsidies CSI_{Solar} = Case Study Solar Incentives NC = New Roofing Construction "IF_{Solar}" and "PS_{Solar}" will both be set to zero in this case study, since only the case study incentives will be included.

Model Parameter	*Feasibility of Government Support*
Parameter Formula	$\frac{(GDP)(1 - IF_{Green} - IF_{Solar}) - PS_{Green} - PS_{Solar} - CSI_{Green} - CSI_{Solar}}{GDP}$
Comments	IF_{Green} = Green GDP Investment Fraction PS_{Green} = Private Green Subsidies IF_{Solar} = Solar GDP Investment Fraction PS_{Solar} = Private Solar Subsidies The "IF" and "PS" variables in this formula will all be set to zero in this case study, since only the case study incentives will be included.

Figure H5: Financial Incentives Portion of Economic Sub-Model with Case Study Parameters

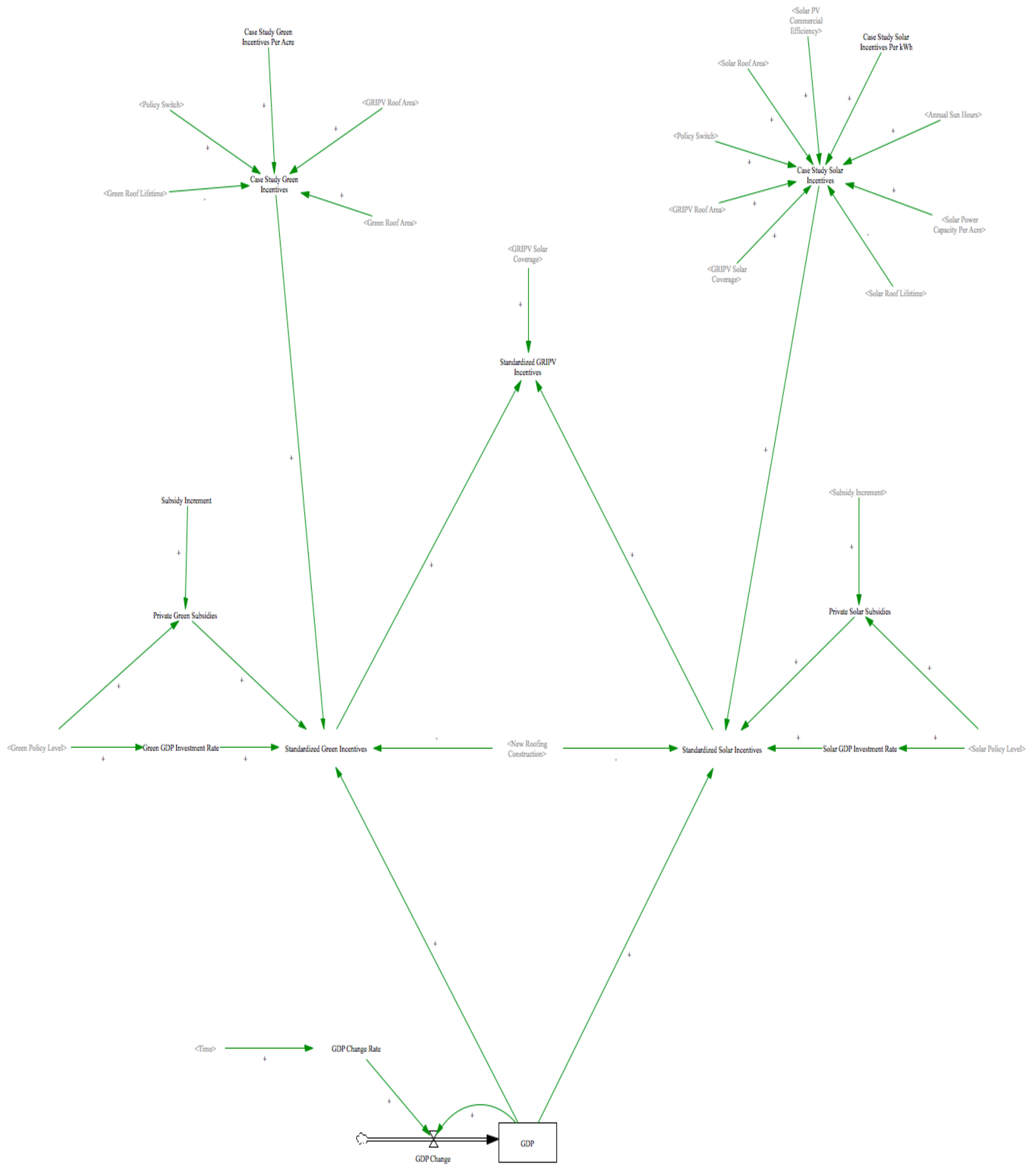


Table H11: Additional Uniform Distributions for Case Study Uncertainty Analysis

Model Parameter	*Minimum Value*	*Maximum Value*
Case Study Green Incentives Per Acre	78,408 USD/Acre	588,080 USD/Acre
Case Study Solar Incentives Per kWh	0.01 USD/kWh	0.21 USD/kWh
Green Bylaw Switch	0	1
Solar Bylaw Switch	0	1
GRIPV Bylaw Switch[1]	0	1

[1]This distribution is only included in the BAU+GRIPV (GRIPV-Only) uncertainty analysis.

APPENDIX I:
ADDITIONAL POLICY ANALYSIS GRAPHS

Figure I1: Conventional Roof Area Individual Policy Results

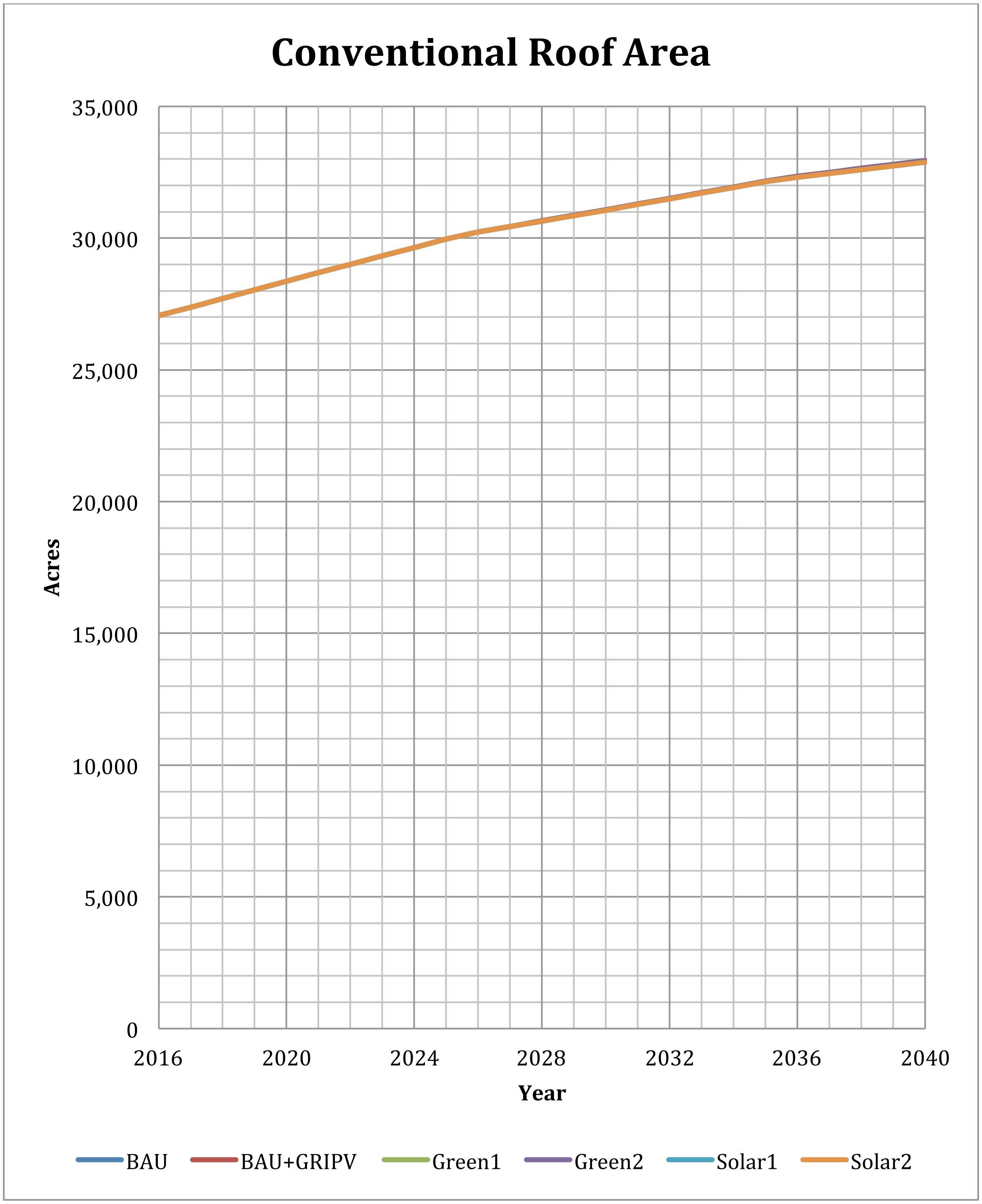


Figure I2: Conventional Roof Area Multiple Policy Results

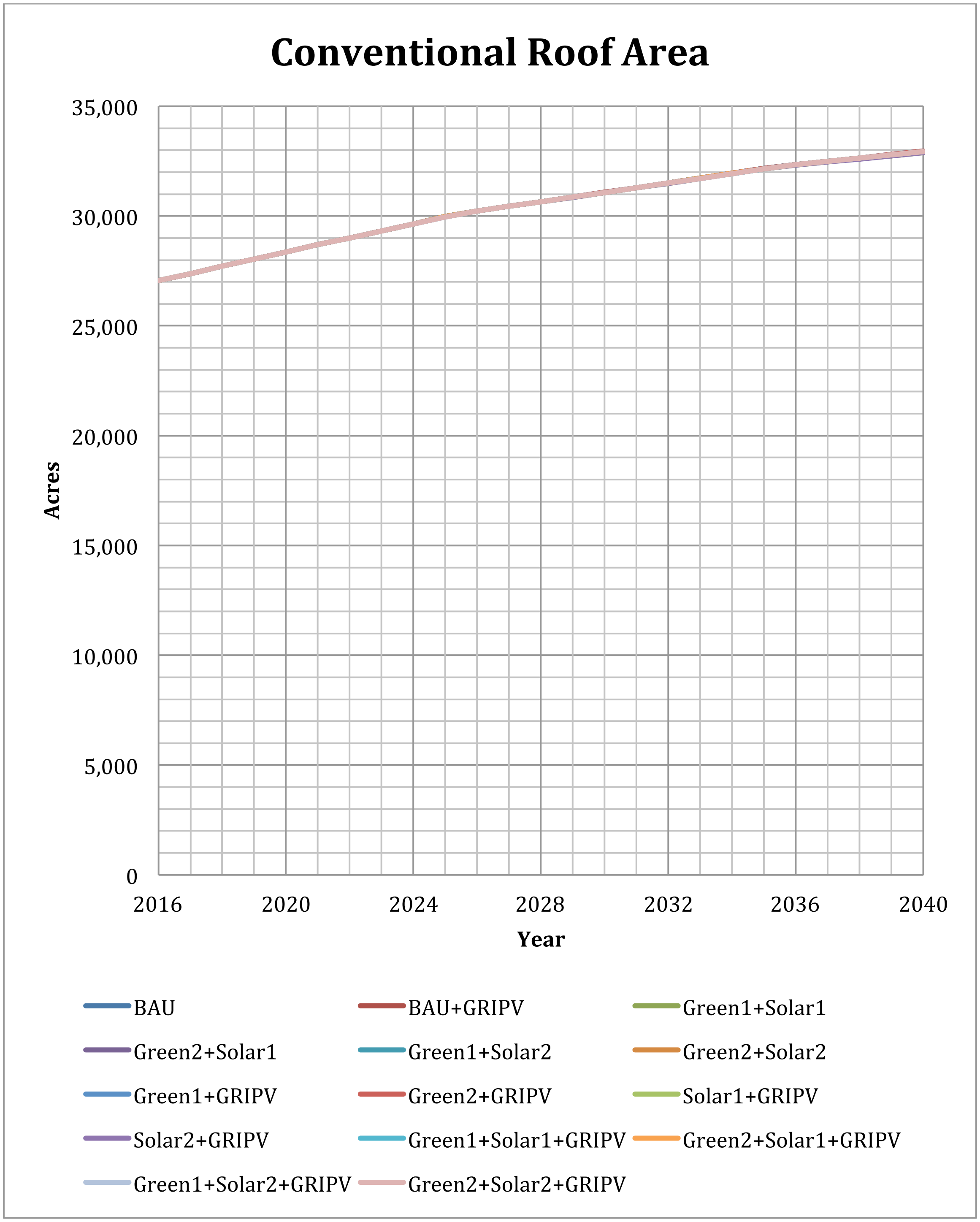


Figure I3: Total Runoff Individual Policy Results

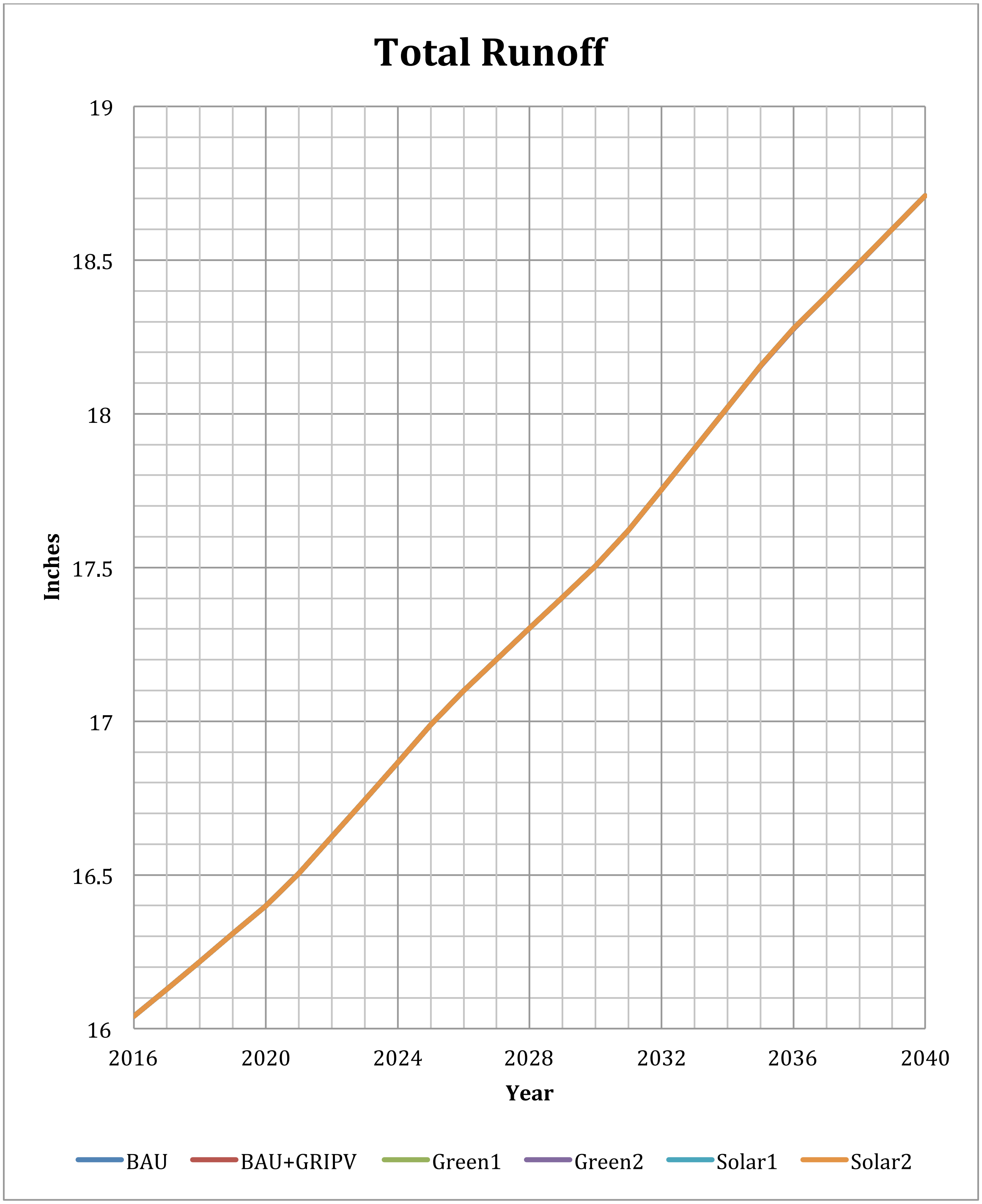


Figure I4: Total Runoff Multiple Policy Results

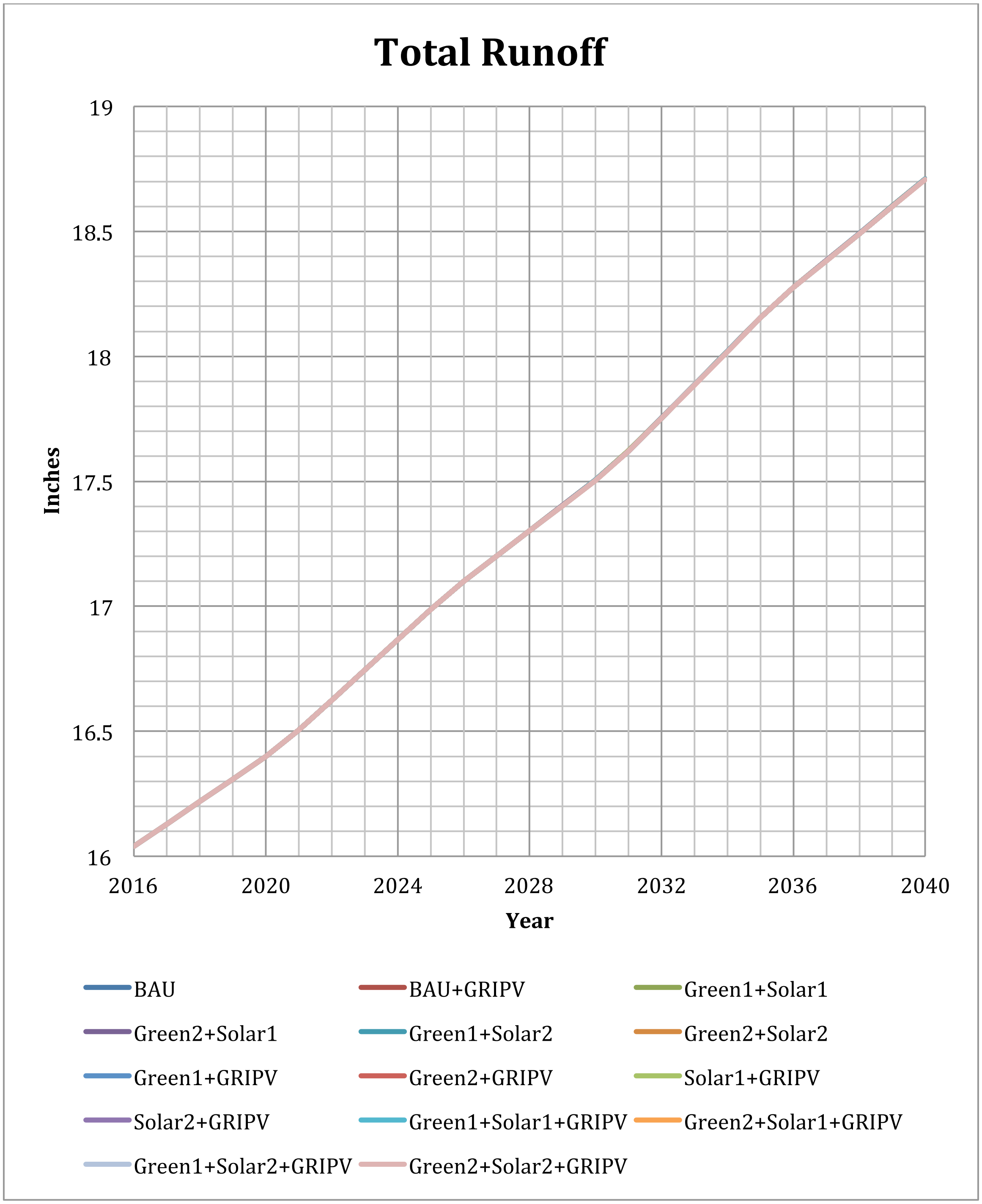


Figure I5: Actual Air Temperature Anomaly Individual Policy Results

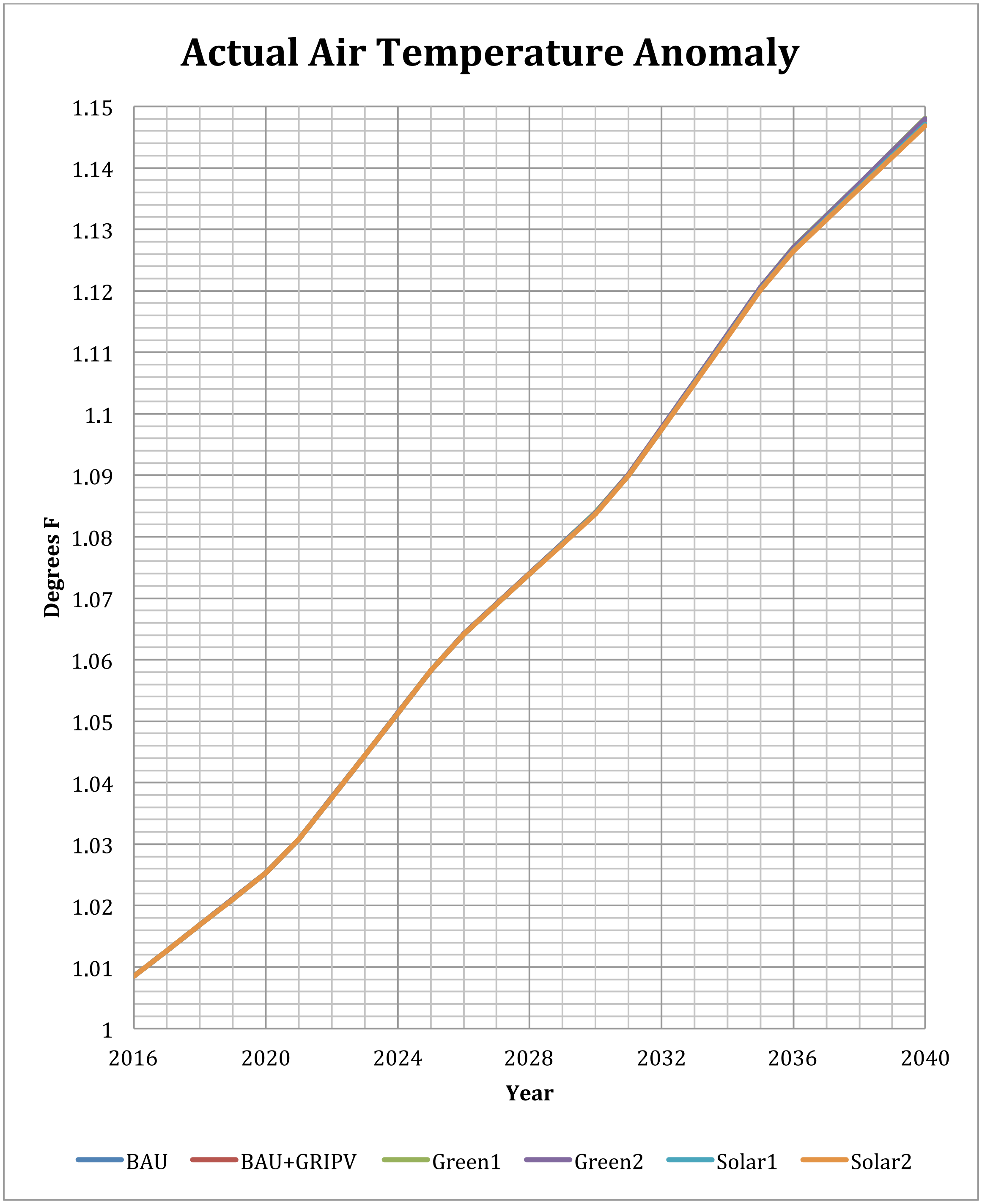
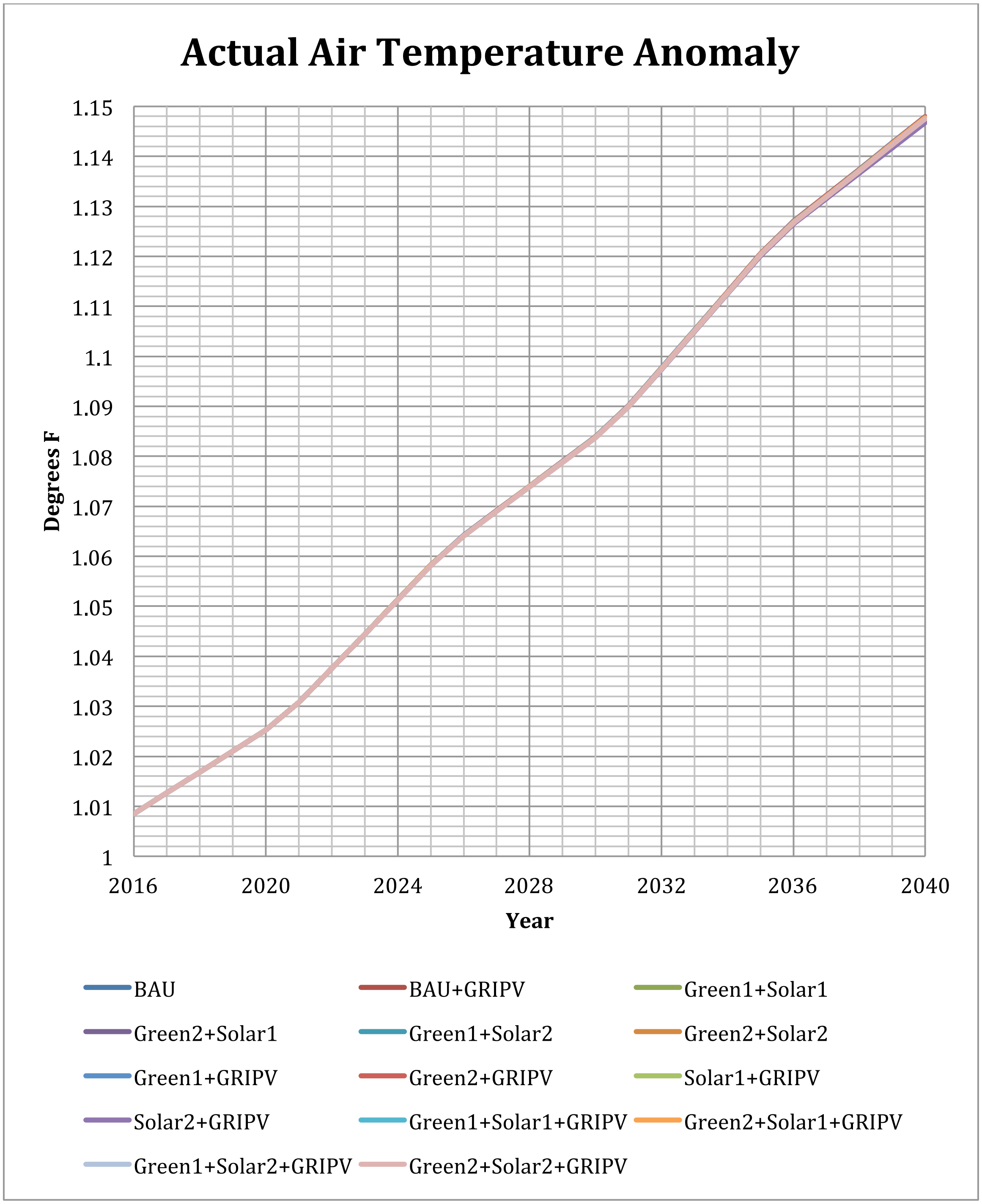


Figure I6: Actual Air Temperature Anomaly Multiple Policy Results



APPENDIX J:
ADDITIONAL UNCERTAINTY ANALYSIS GRAPHS

Figure J1: Total Runoff BAU Uncertainty Graph

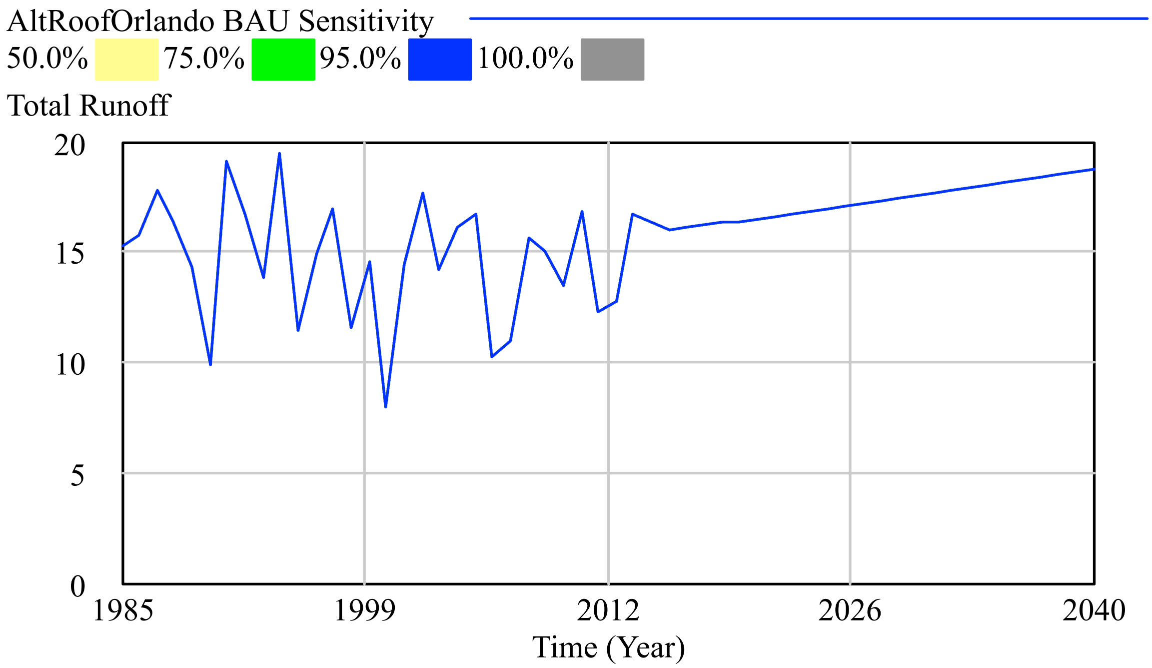


Figure J2: Total Runoff GRIPV-Only Uncertainty Graph

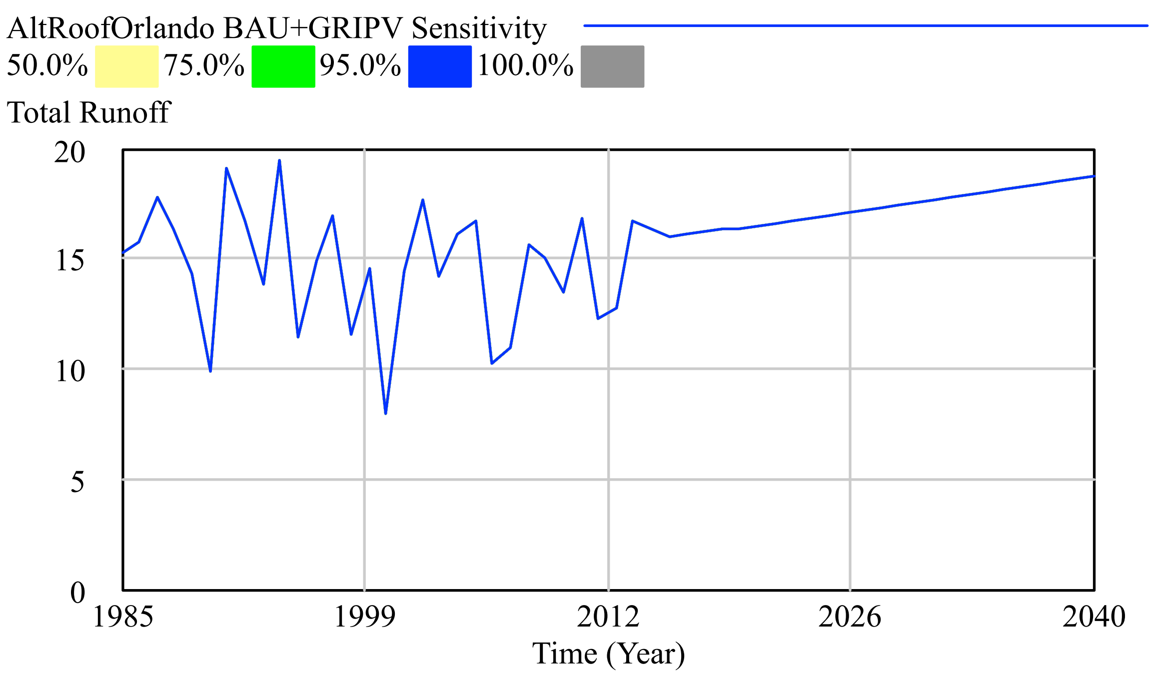


Figure J3: Conventional Roof Area Histograms

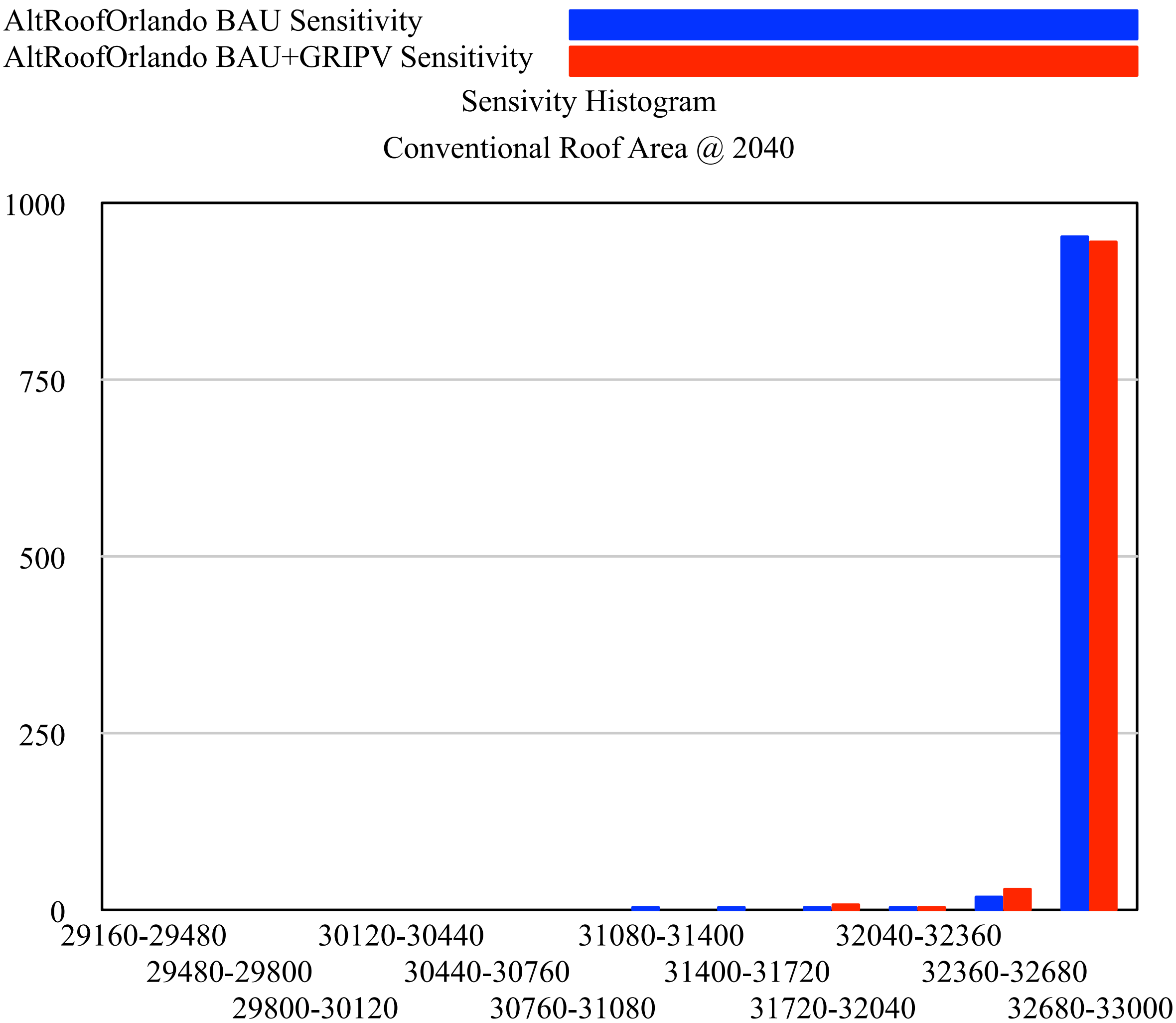


Figure J4: Green Roof Area Histograms

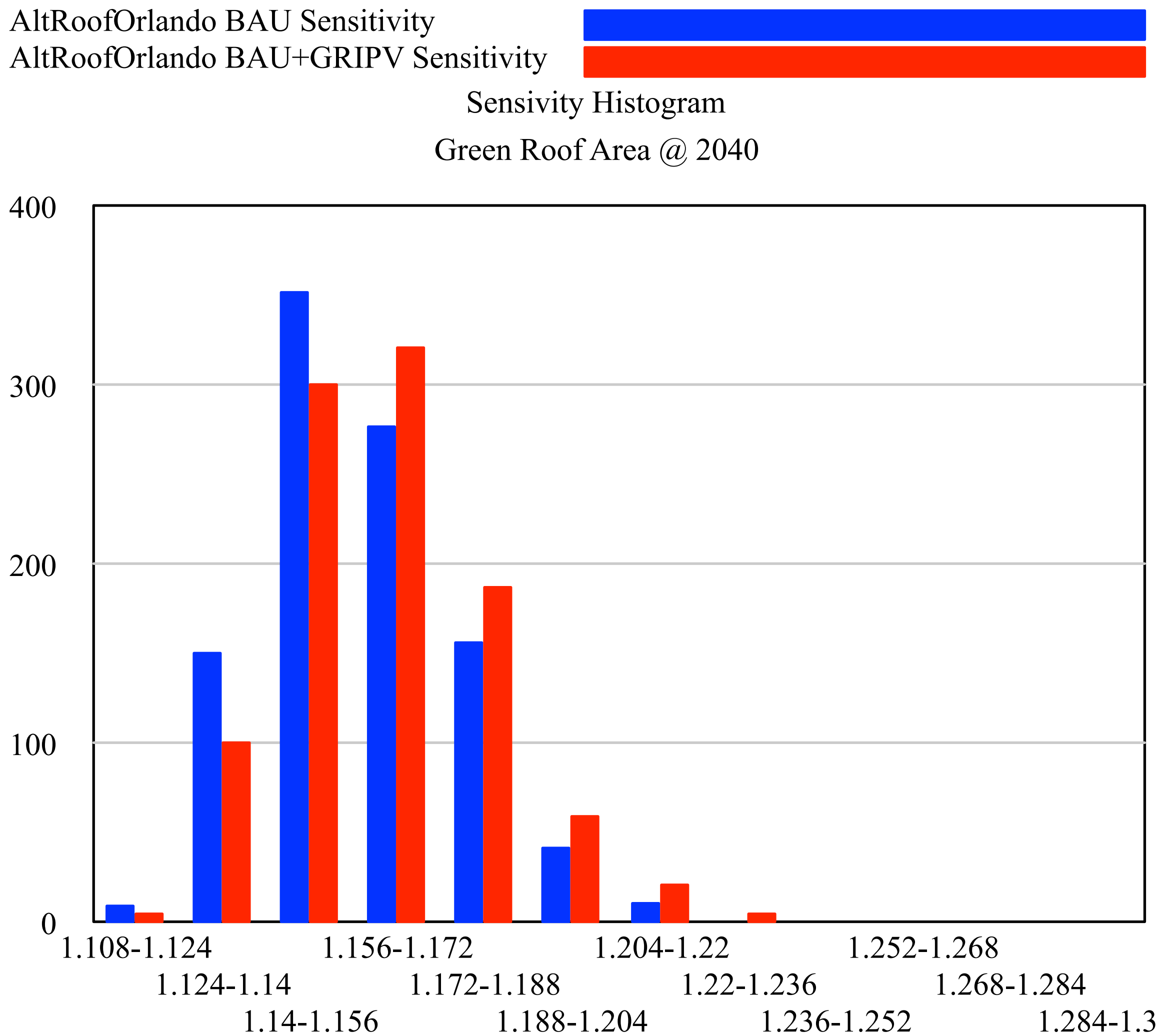


Figure J5: Solar Roof Area Histograms

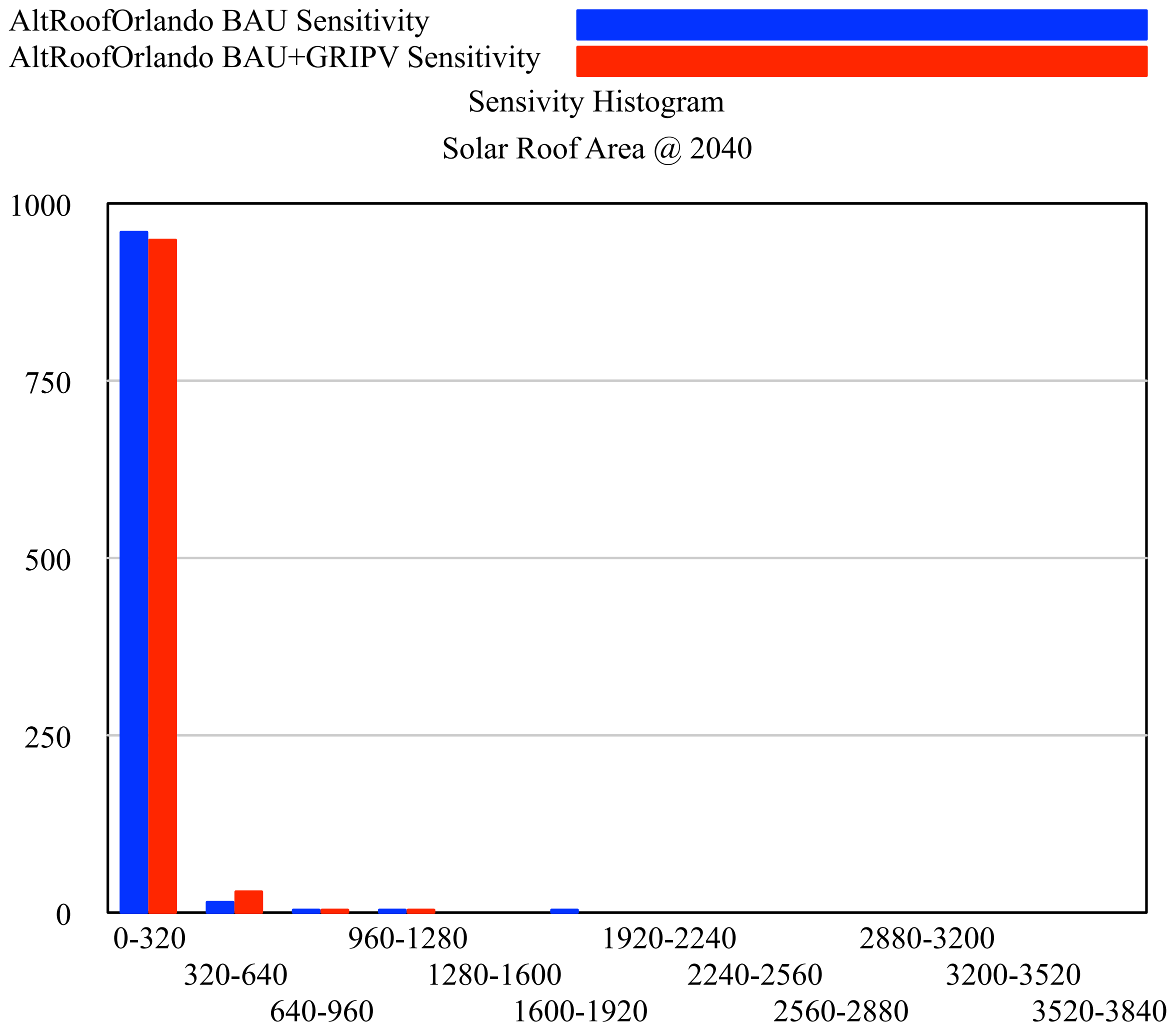


Figure J6: GRIPV Roof Area Histogram

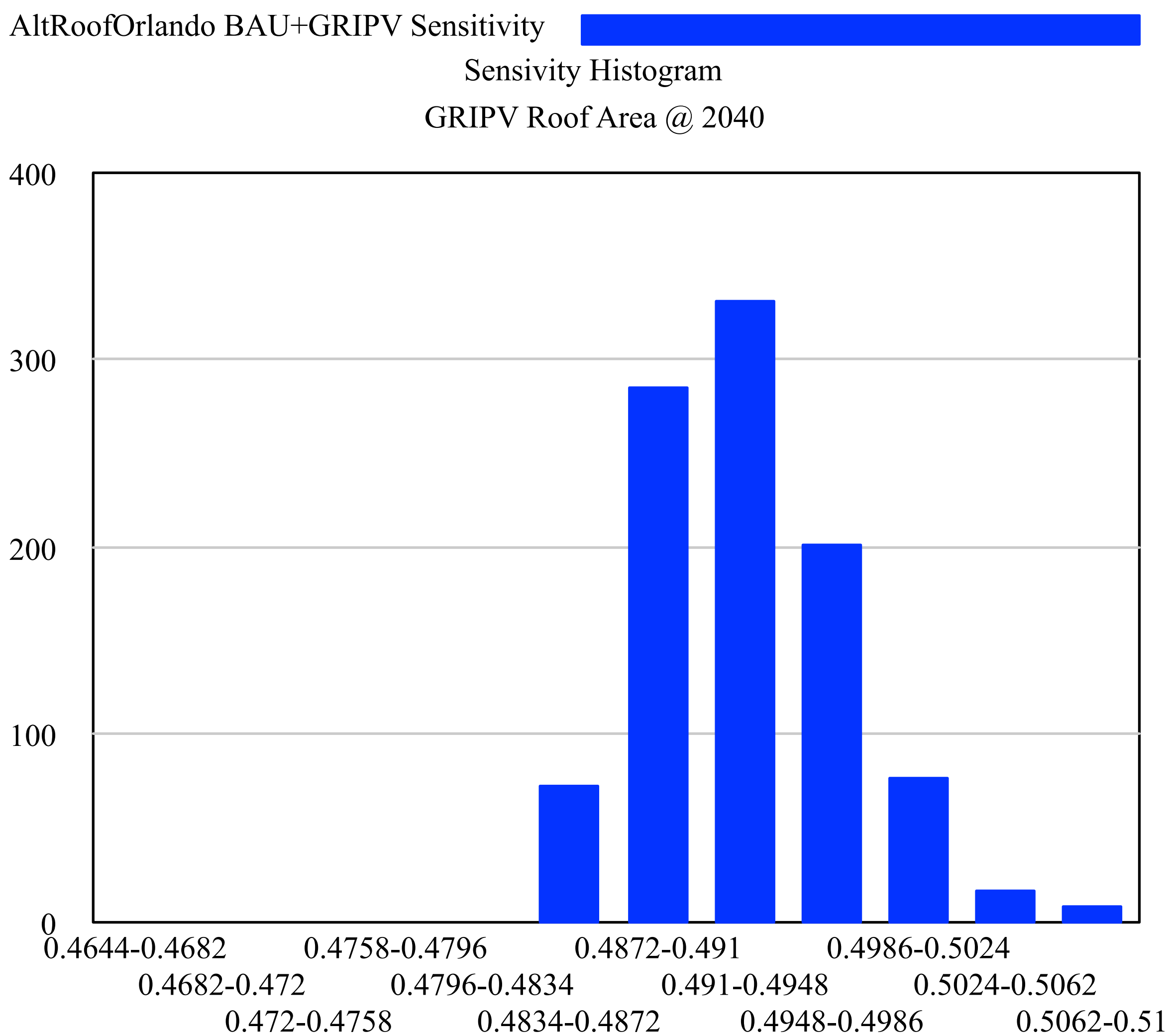


Figure J7: Total Runoff Histograms

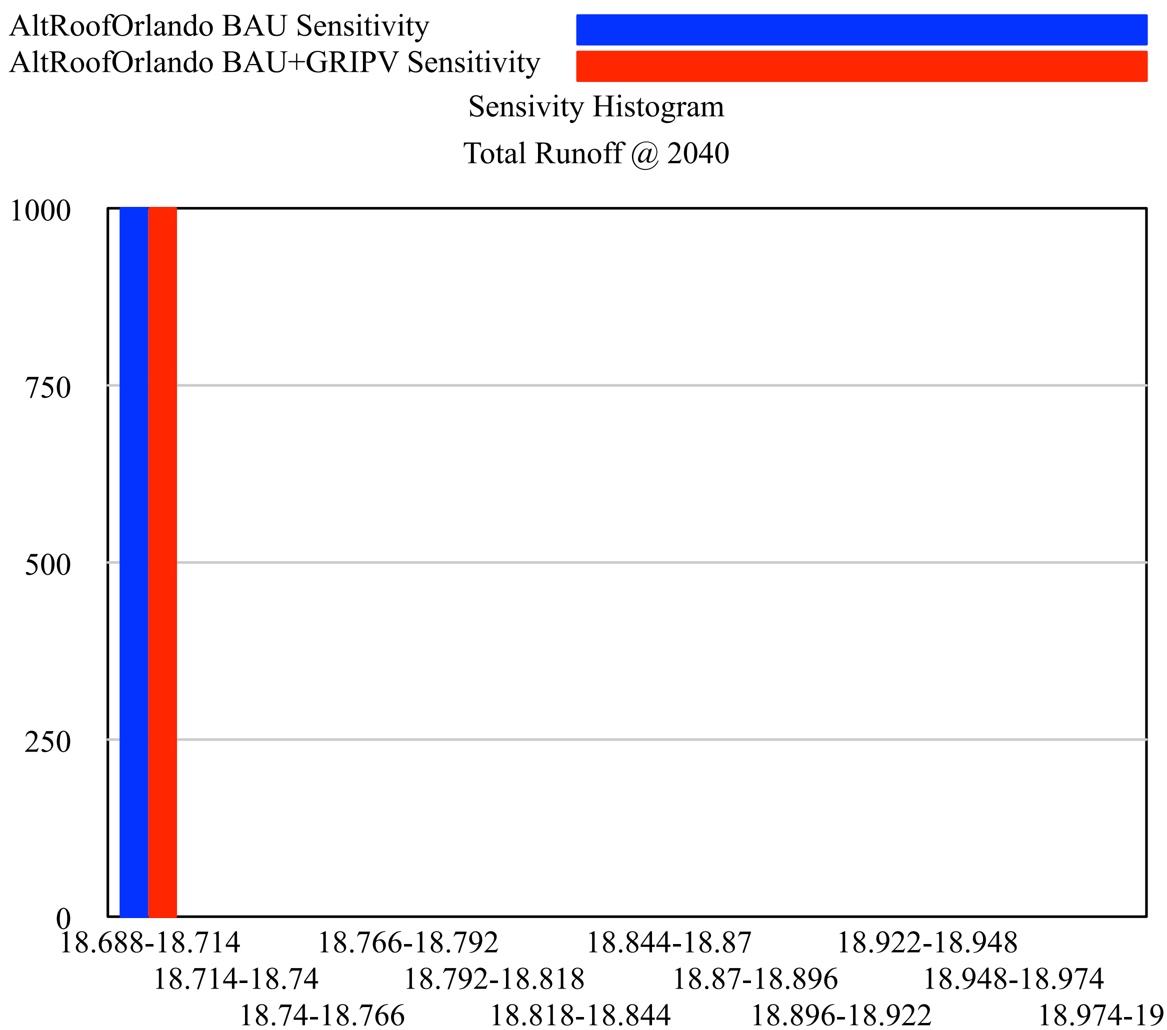


Figure J8: Actual Air Temperature Anomaly Histograms

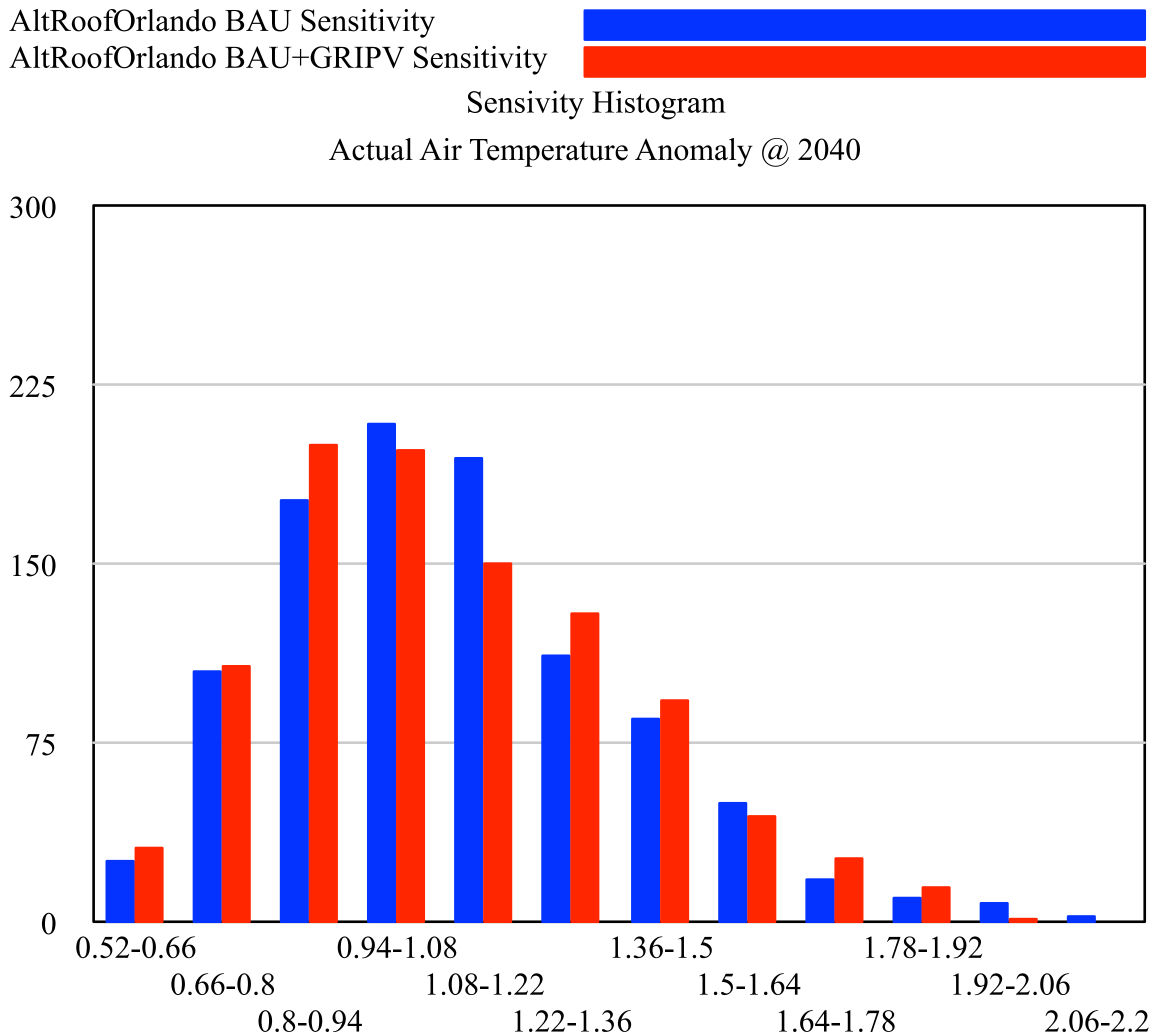


Figure J9: Energy Goal Progress Histograms

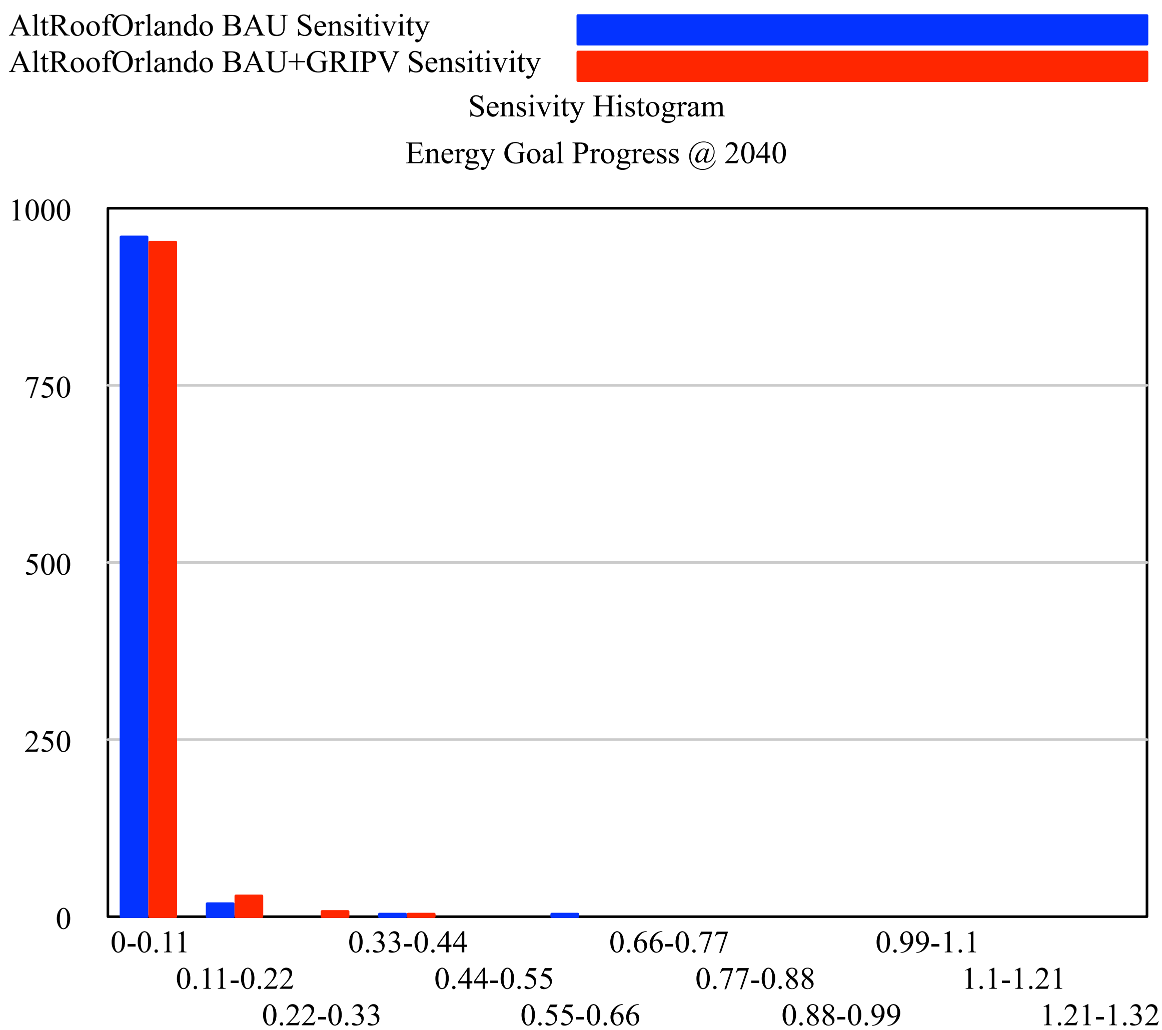
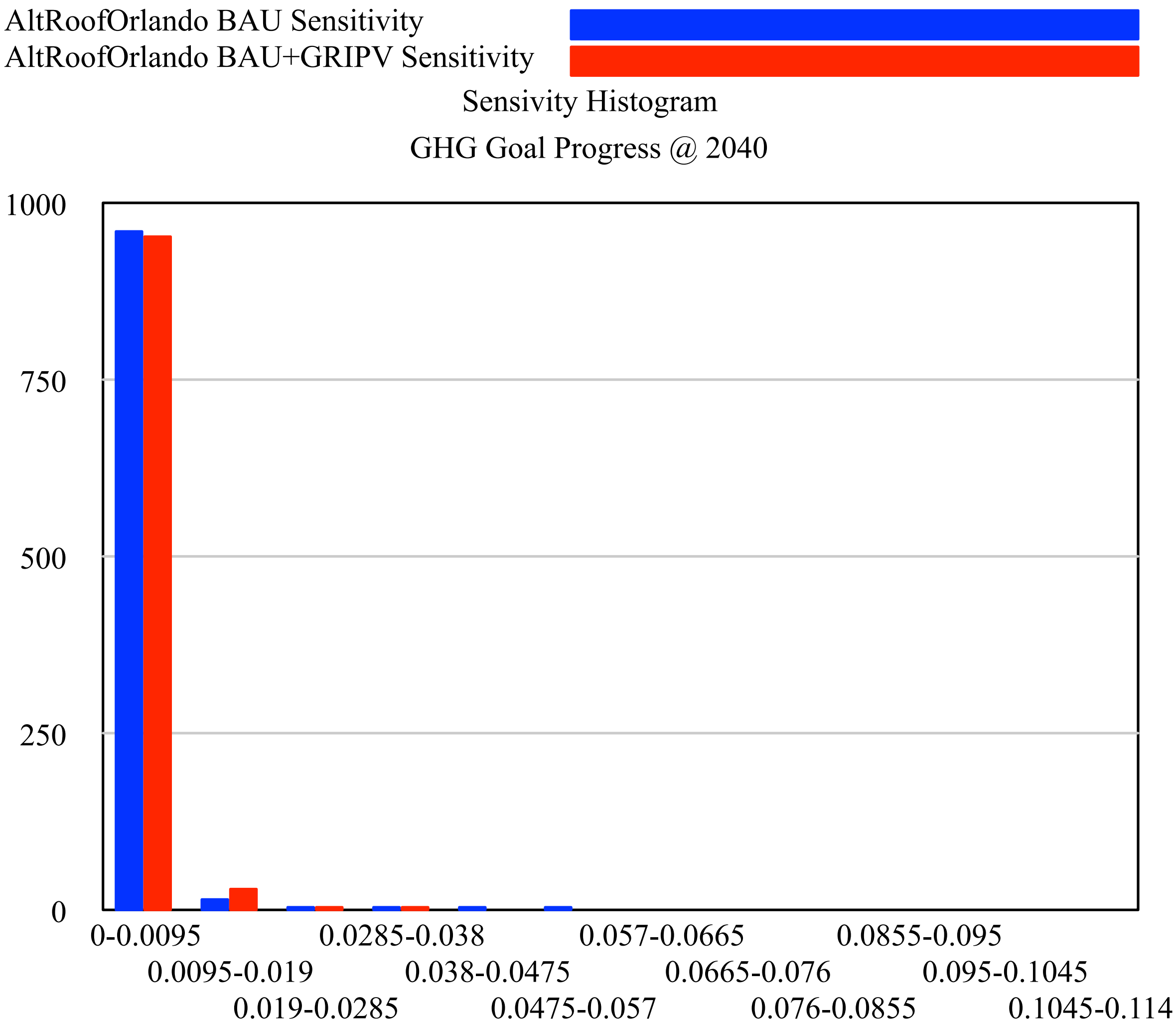


Figure J10: GHG Goal Progress Histograms



APPENDIX K:
ADDITIONAL CASE STUDY ANALYSIS GRAPHS

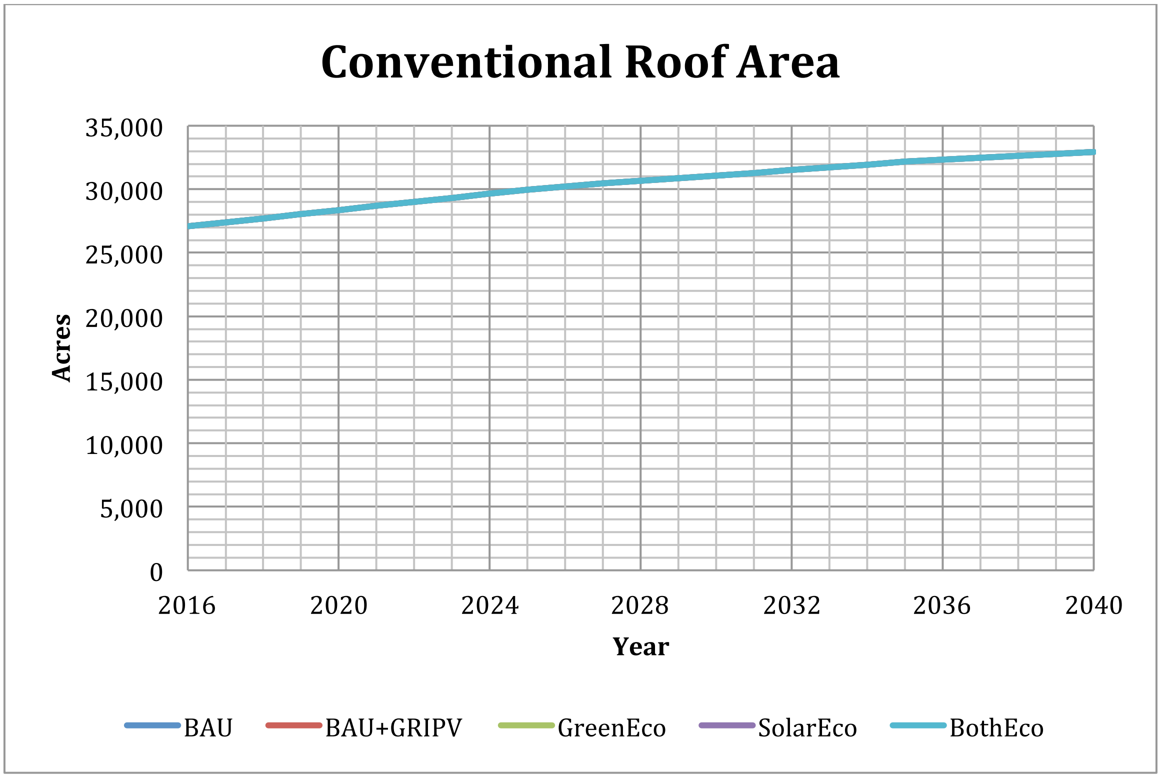


Figure K1: Conventional Roof Area Case Study Policy Results – Financial Incentives Only (No GRIPV Market)

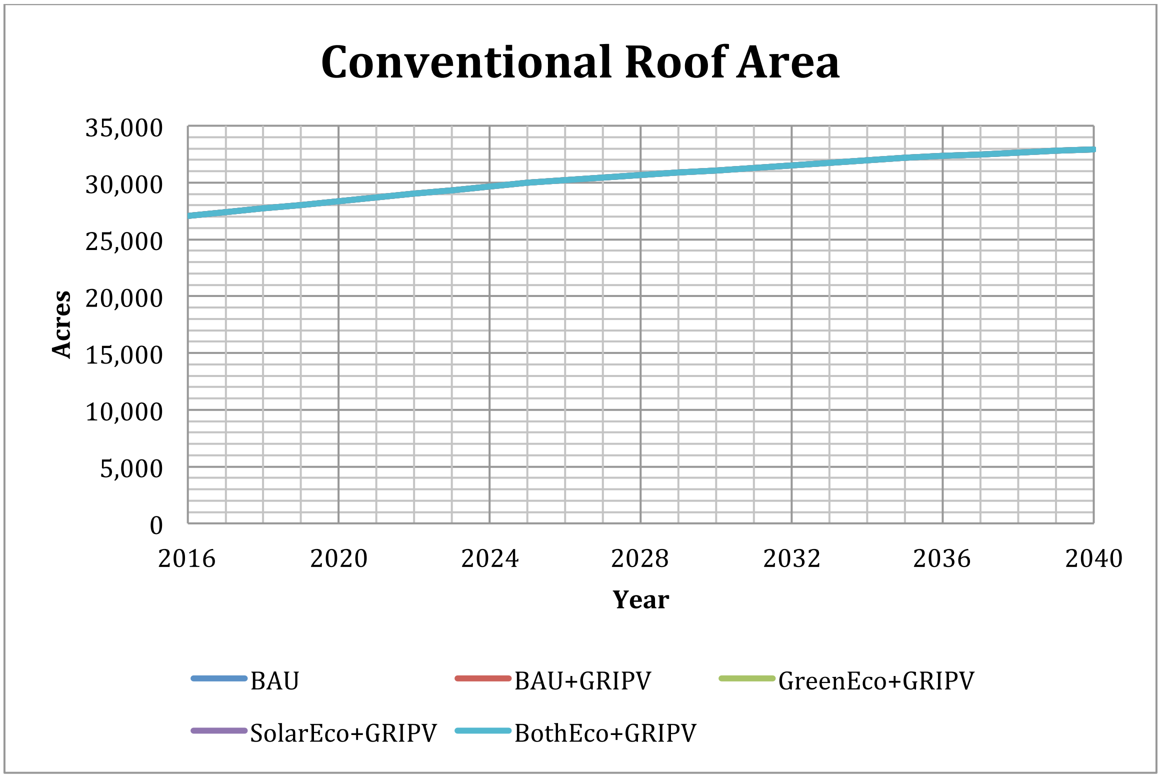


Figure K2: Conventional Roof Area Case Study Policy Results – Financial Incentives Only (GRIPV Included)

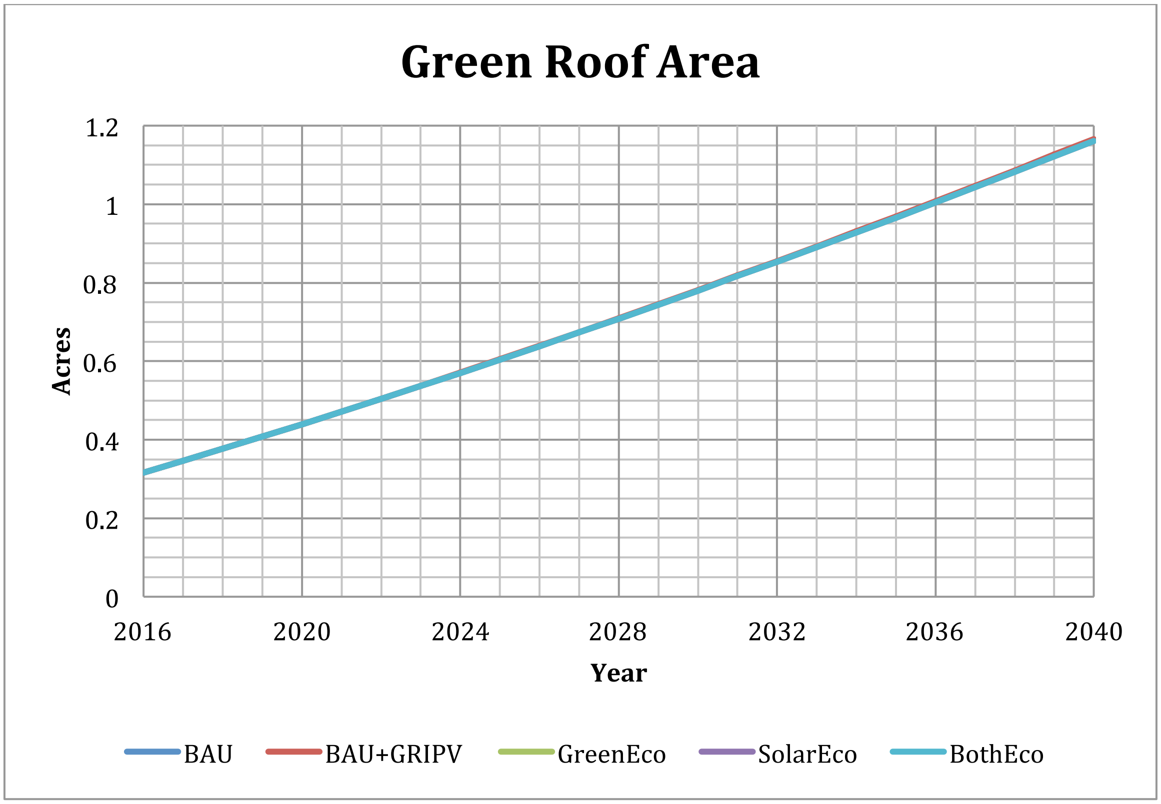


Figure K3: Green Roof Area Case Study Policy Results – Financial Incentives Only

(No GRIPV Market)

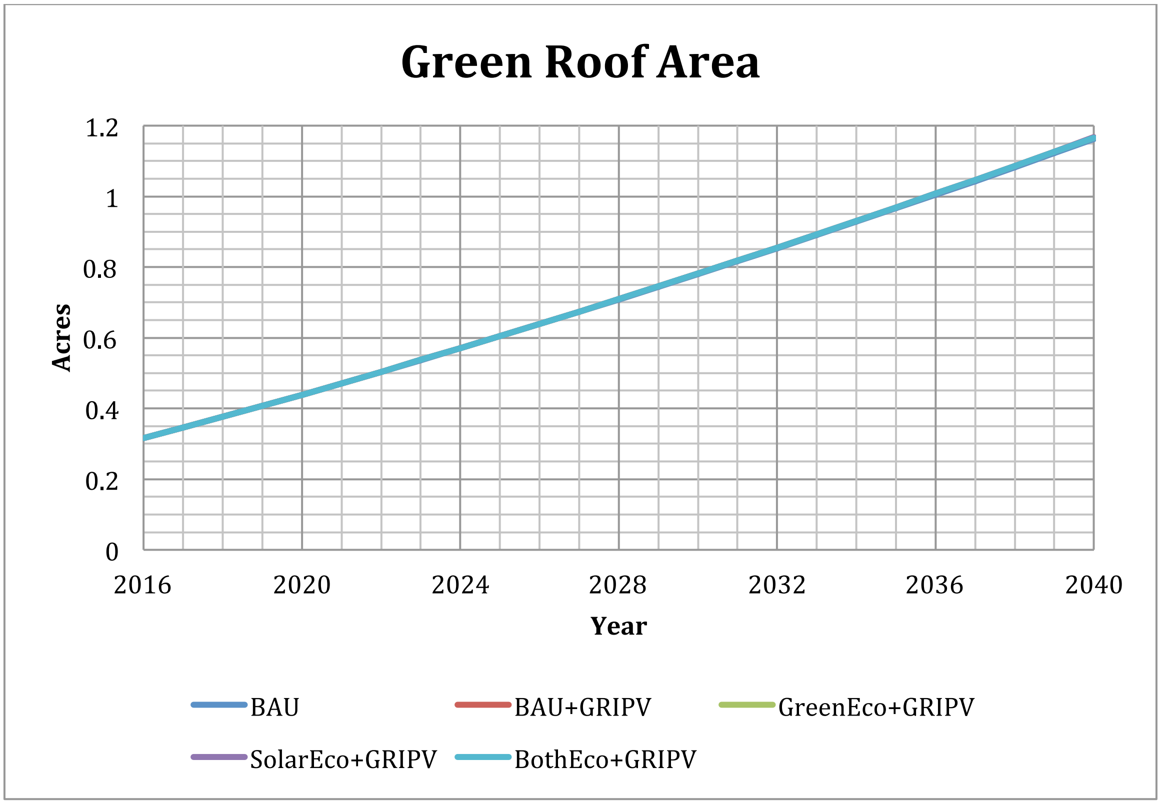


Figure K4: Green Roof Area Case Study Policy Results – Financial Incentives Only

(GRIPV Included)

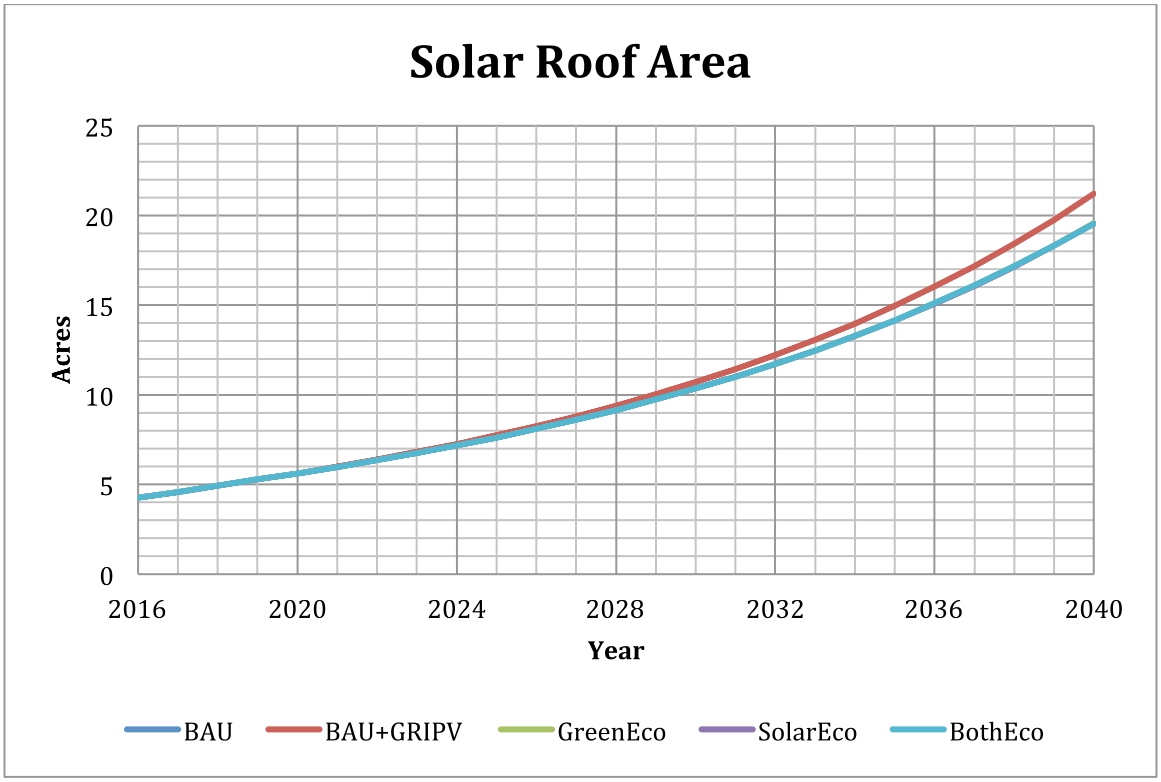


Figure K5: Solar Roof Area Case Study Policy Results – Financial Incentives Only

(No GRIPV Market)

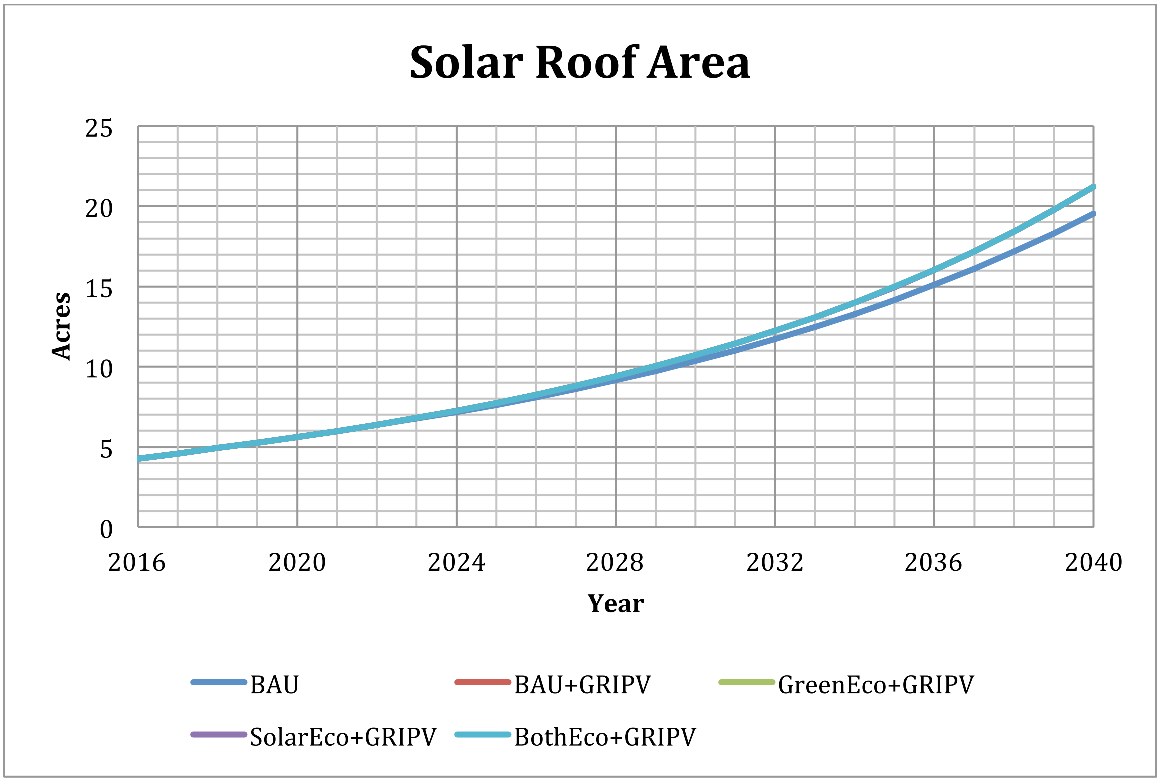


Figure K6: Solar Roof Area Case Study Policy Results – Financial Incentives Only (GRIPV Included)

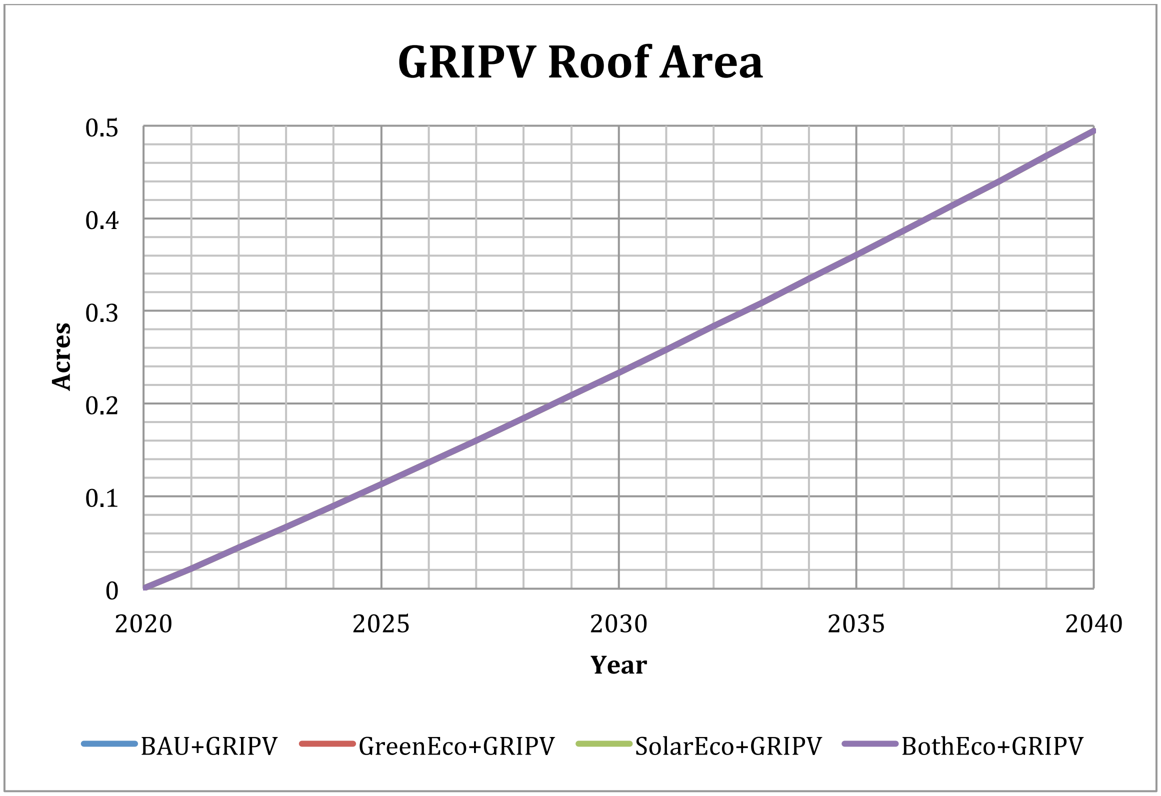


Figure K7: GRIPV Roof Area Case Study Policy Results – Financial Incentives Only

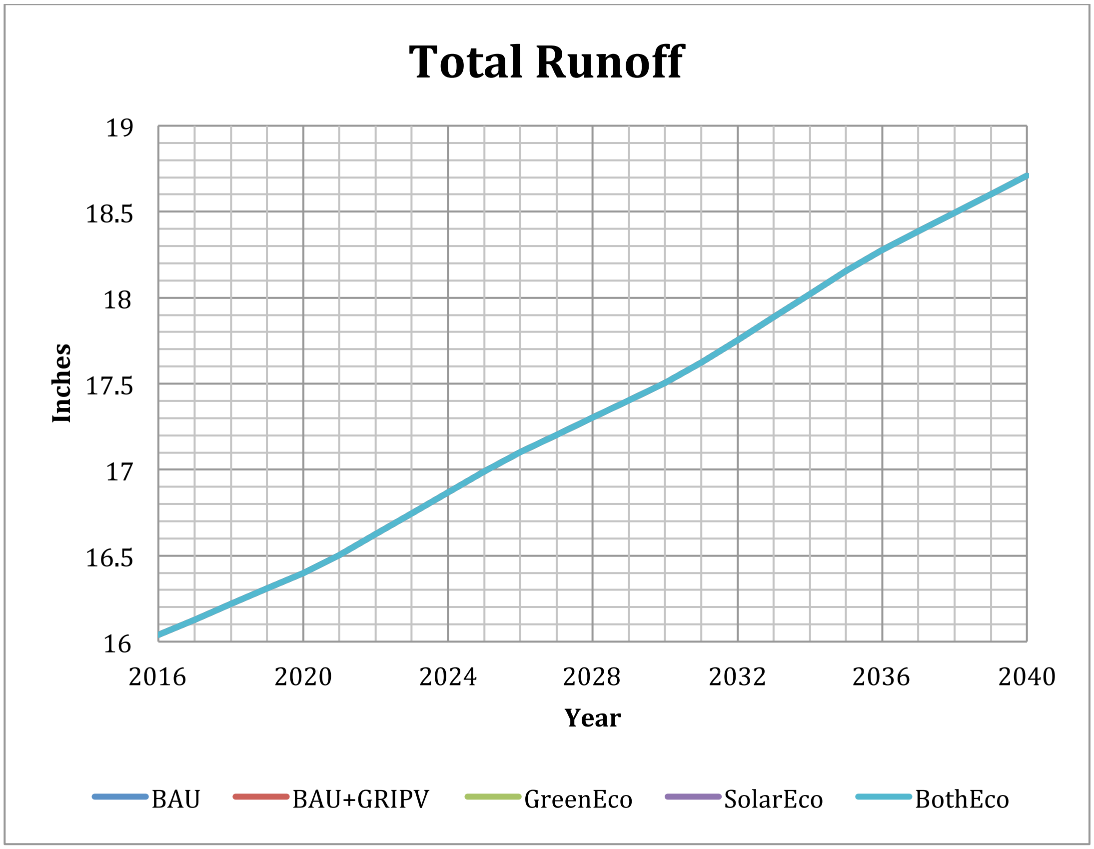


Figure K8: Total Runoff Case Study Policy Results – Financial Incentives Only

(No GRIPV Market)

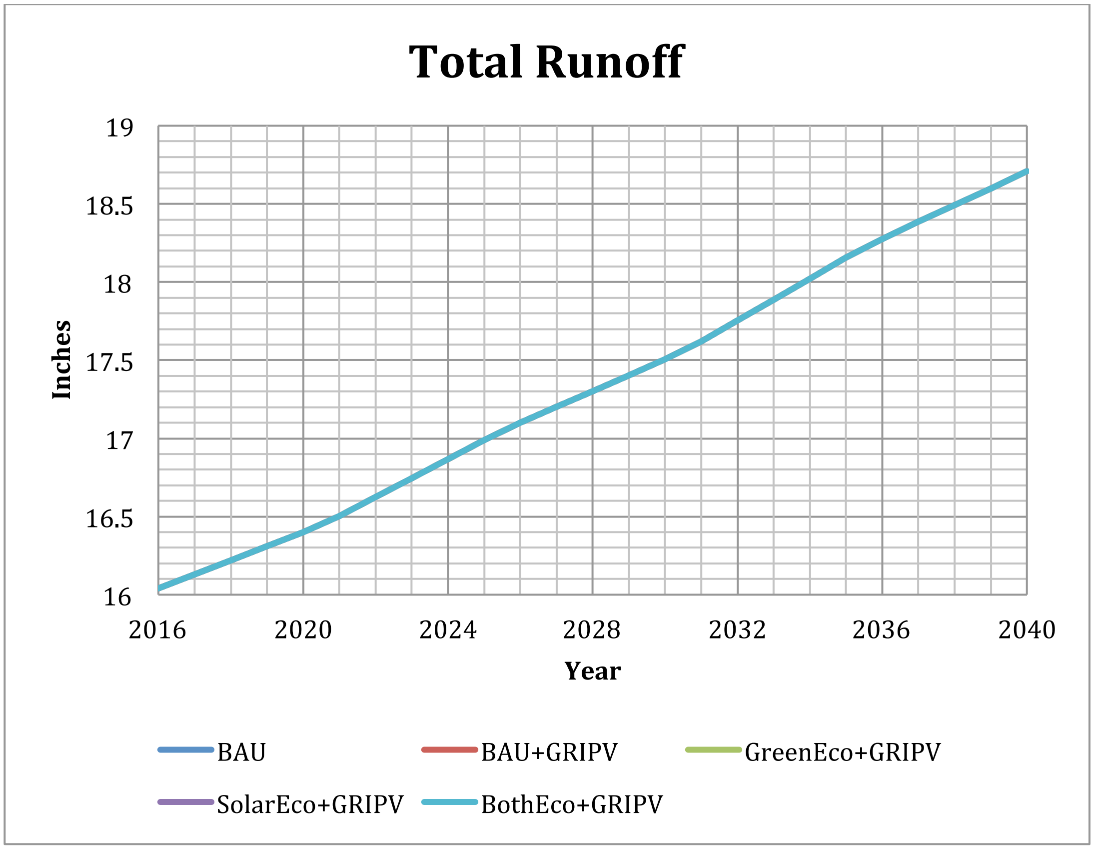


Figure K9: Total Runoff Case Study Policy Results – Financial Incentives Only

(GRIPV Included)

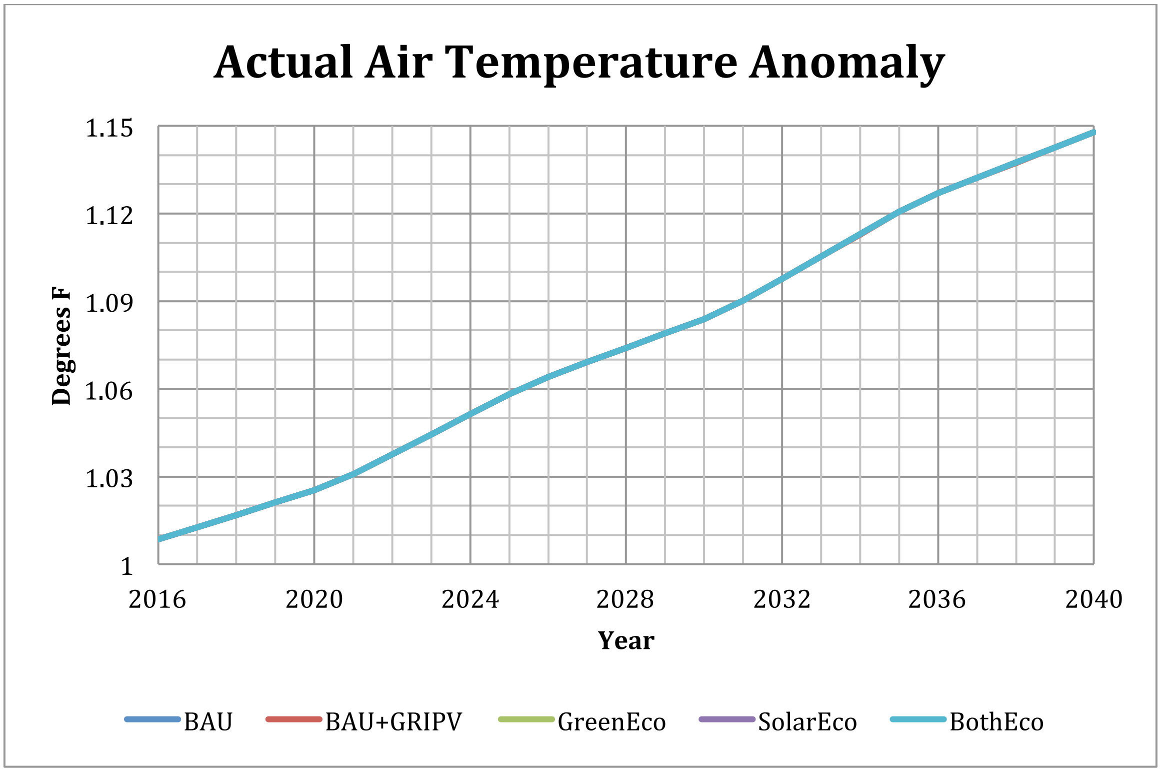


Figure K10: Air Temperature Anomaly Case Study Policy Results – Financial Incentives Only

(No GRIPV Market)

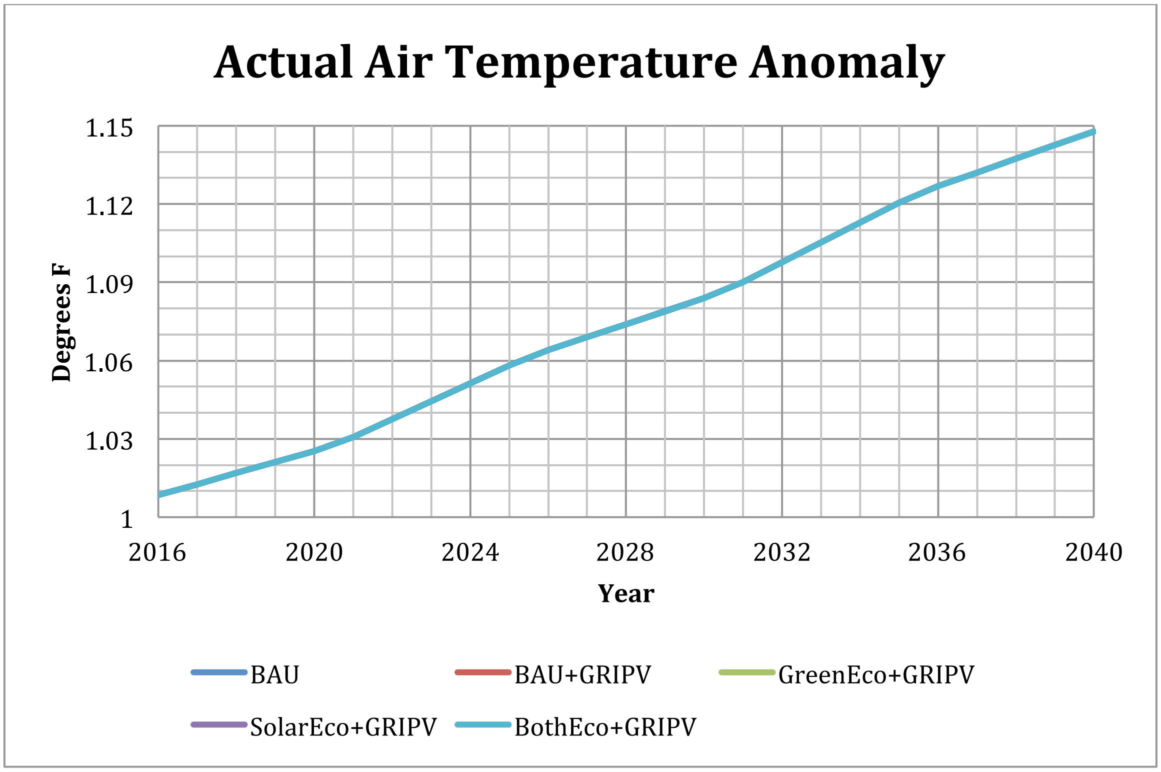


Figure K11: Air Temperature Anomaly Case Study Policy Results – Financial Incentives Only (GRIPV Included)

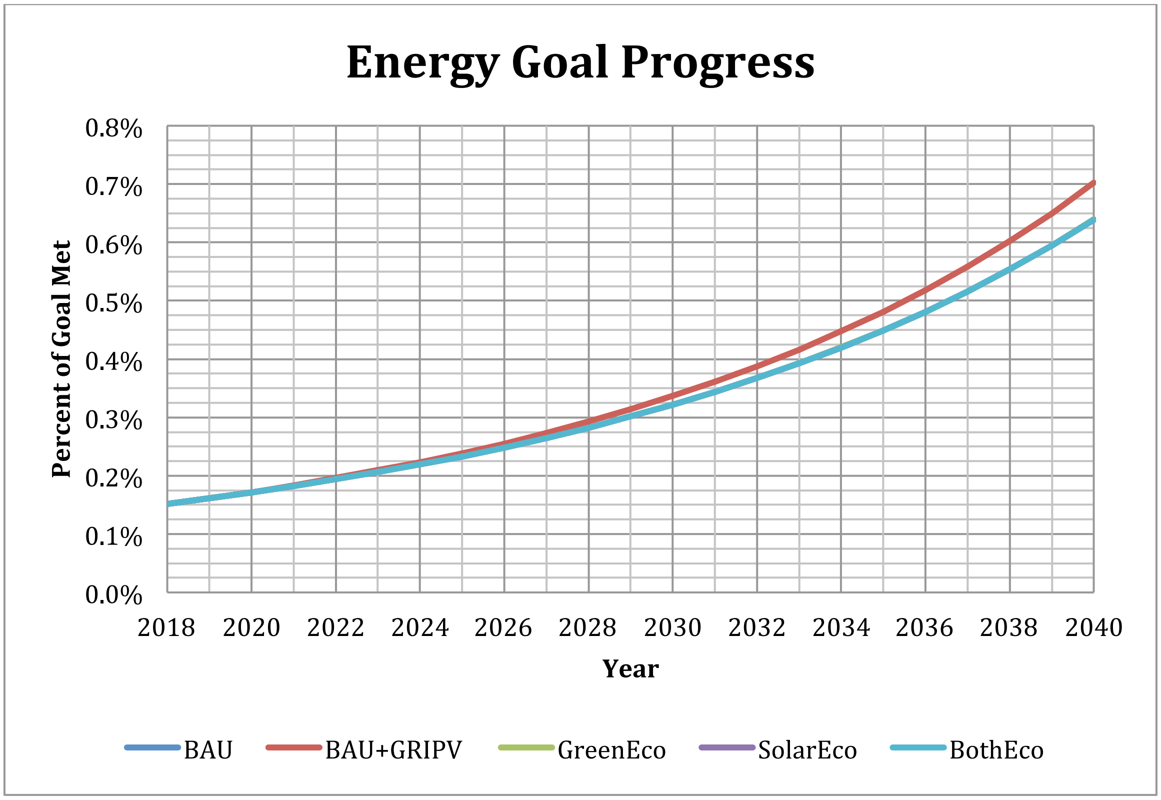


Figure K12: Energy Goal Progress Case Study Policy Results – Financial Incentives Only (No GRIPV Market)

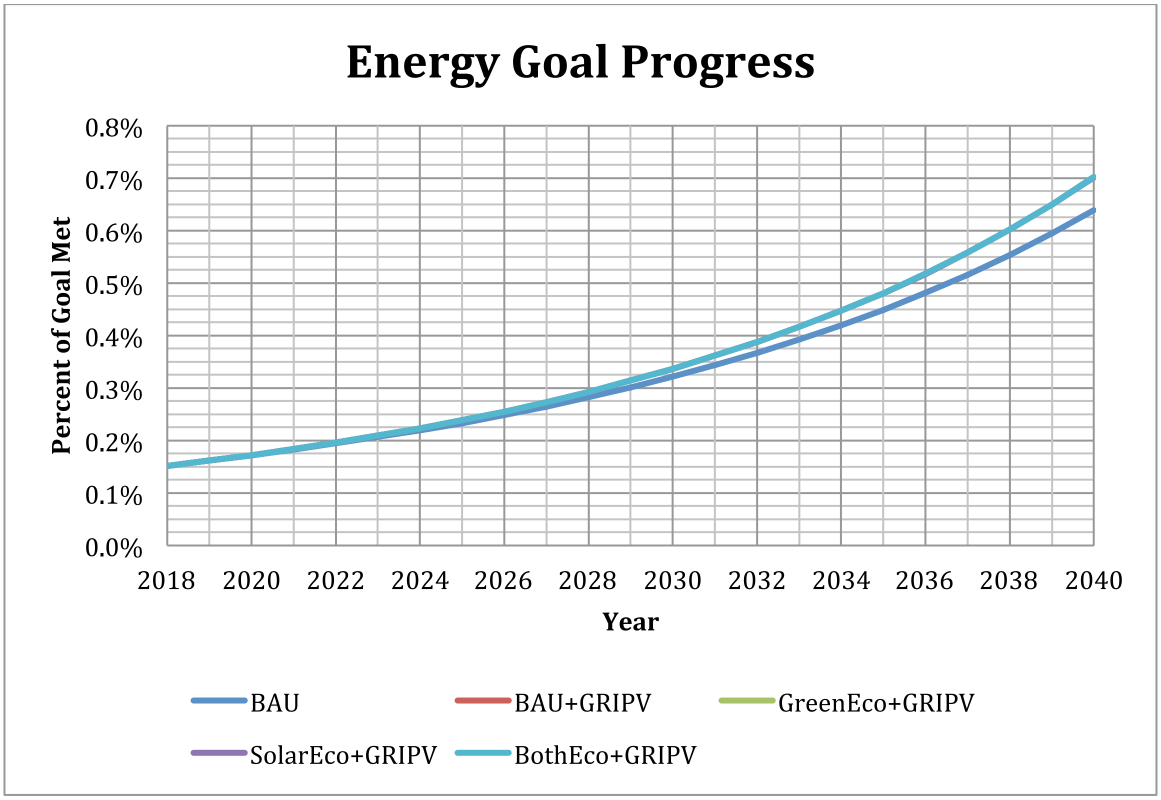


Figure K13: Energy Goal Progress Case Study Policy Results – Financial Incentives Only

(GRIPV Included)

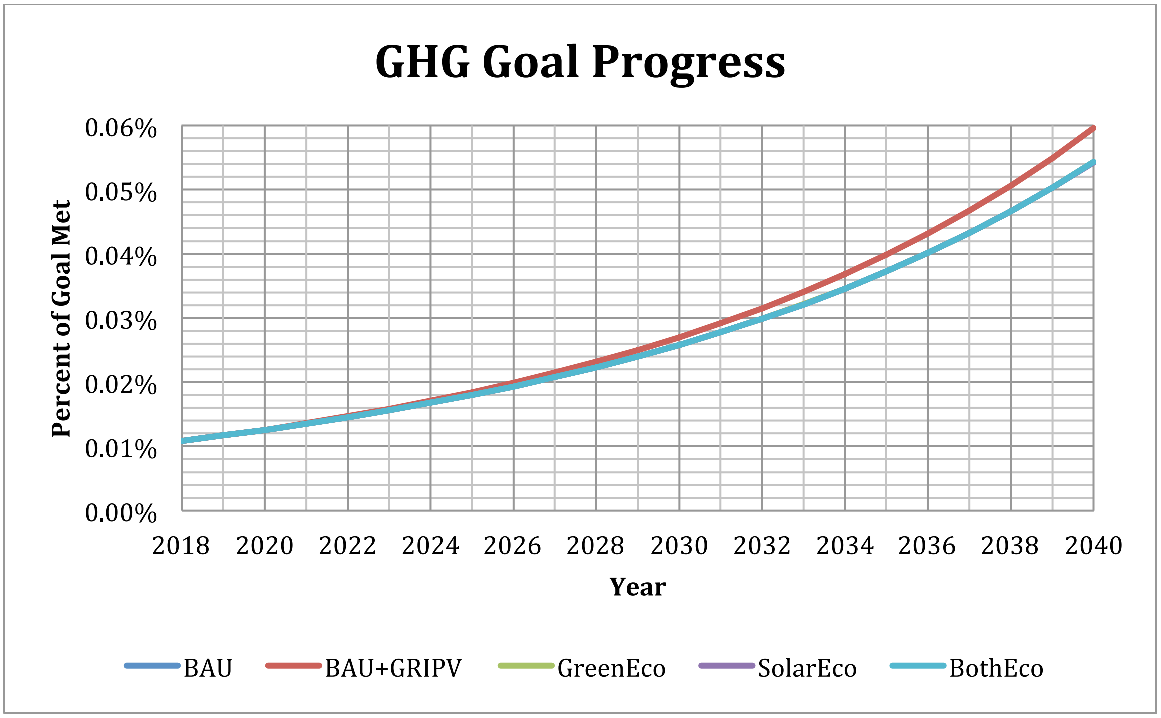


Figure K14: GHG Goal Progress Case Study Policy Results – Financial Incentives Only

(No GRIPV Market)

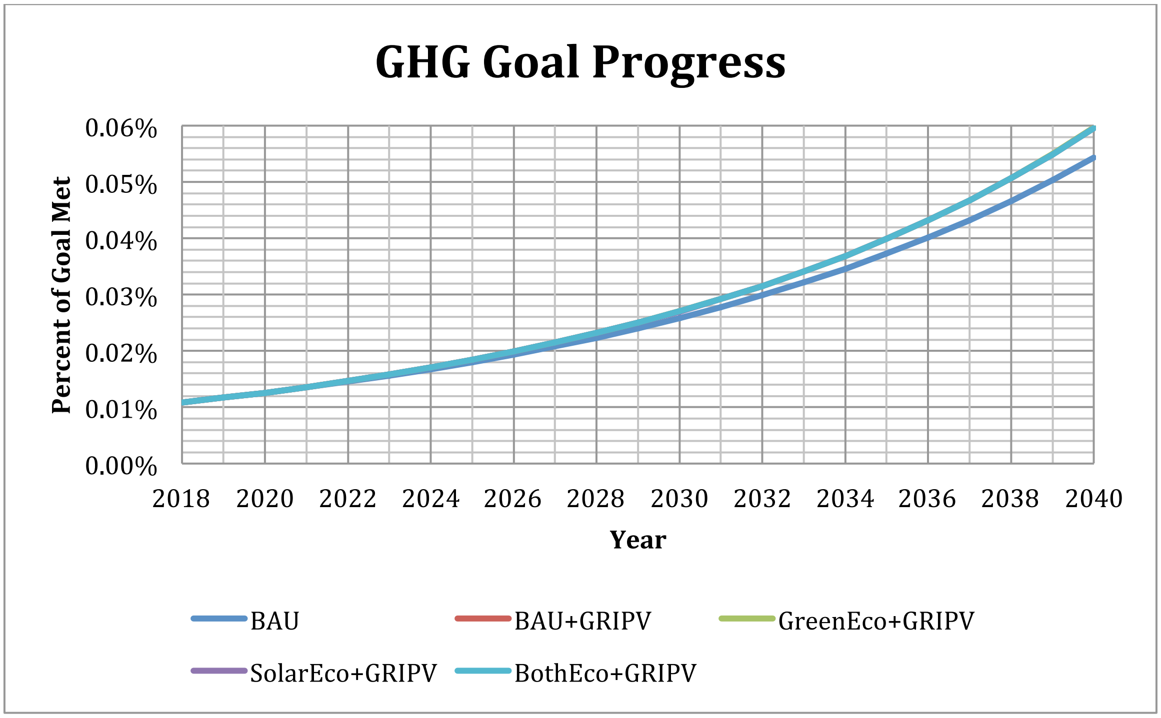


Figure K15: GHG Goal Progress Case Study Policy Results – Financial Incentives Only (GRIPV Included)

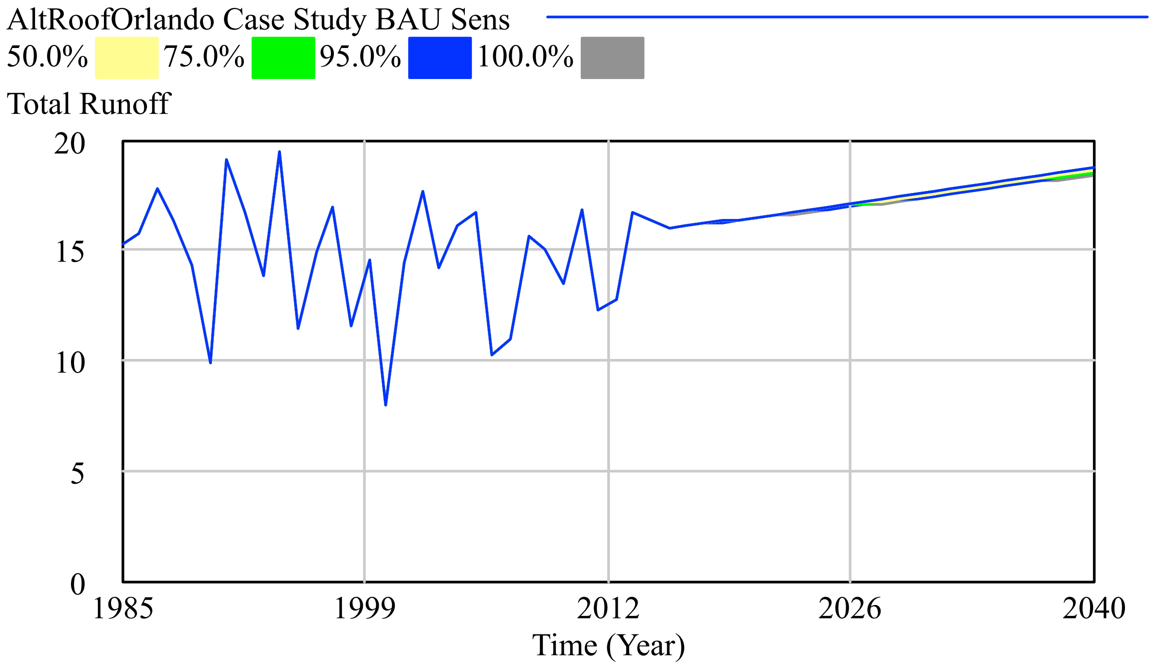


Figure K16: Total Runoff Case Study Uncertainty Graph (No GRIPV Market)

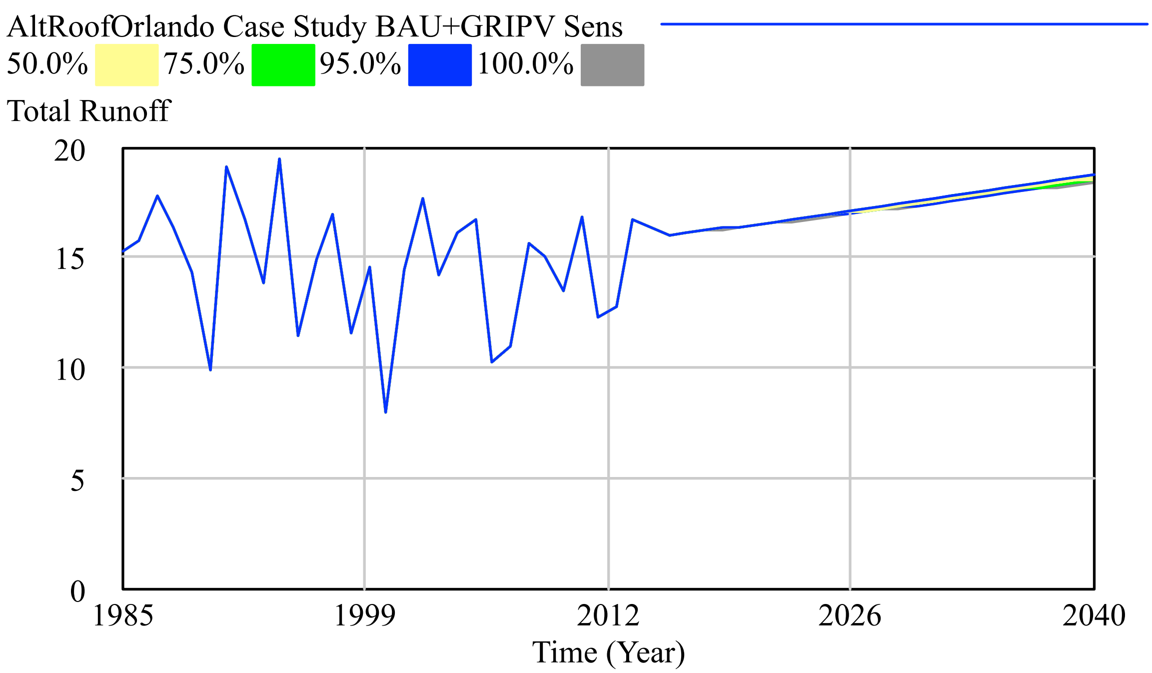


Figure K17: Total Runoff Case Study Uncertainty Graph (GRIPV Included)

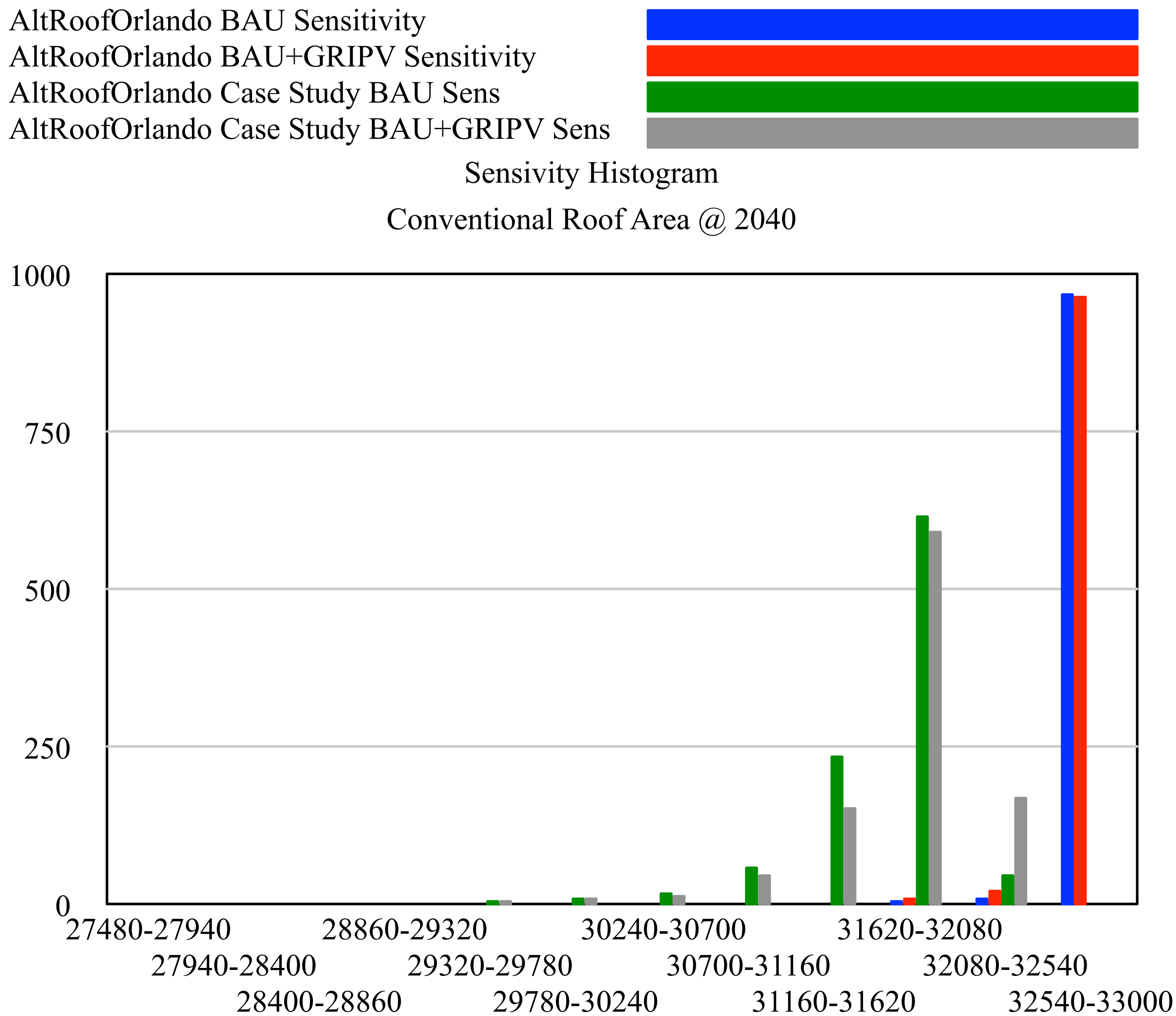


Figure K18: Conventional Roof Area Case Study Histograms

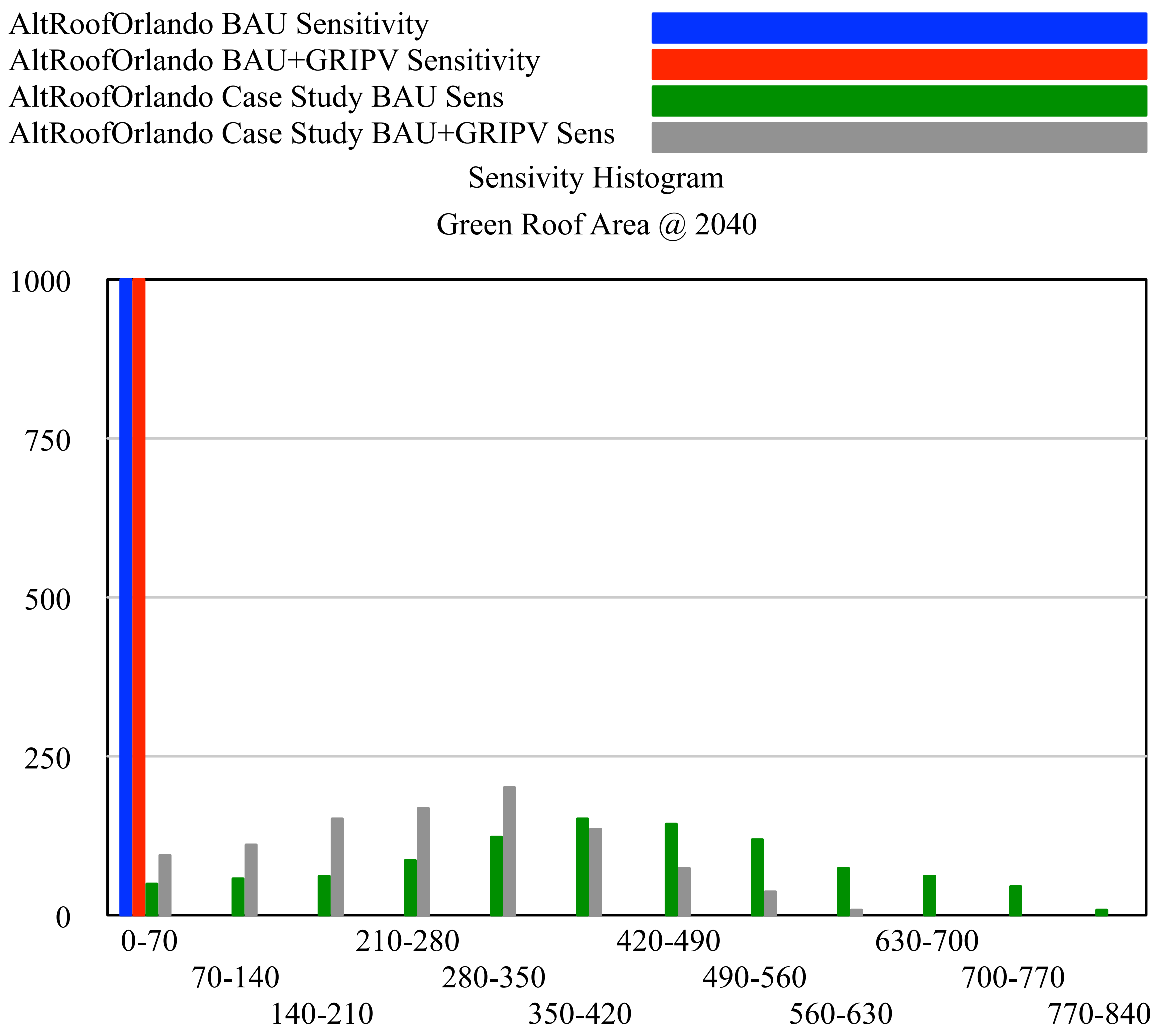


Figure K19: Green Roof Area Case Study Histograms

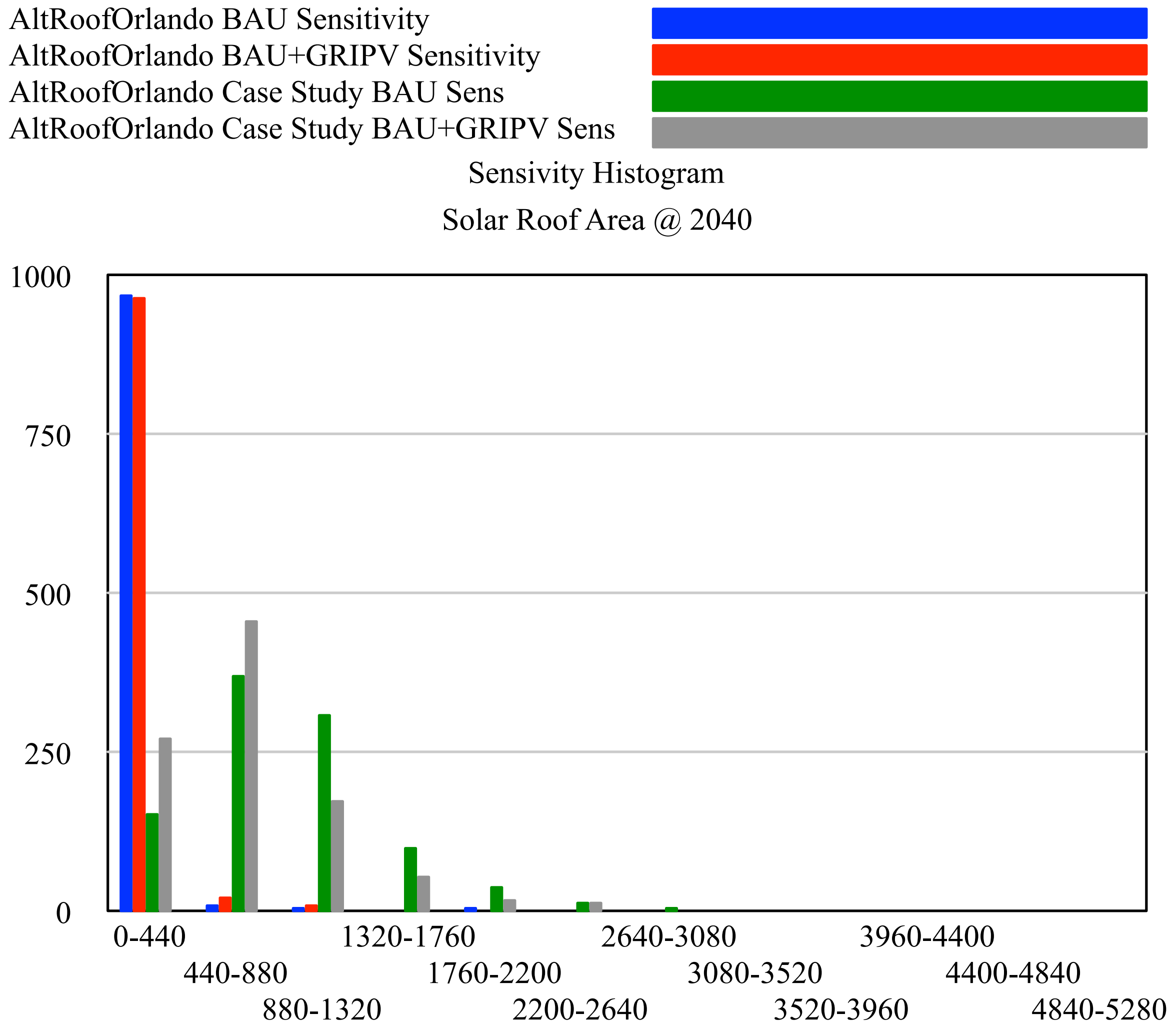


Figure K20: Solar Roof Area Case Study Histograms

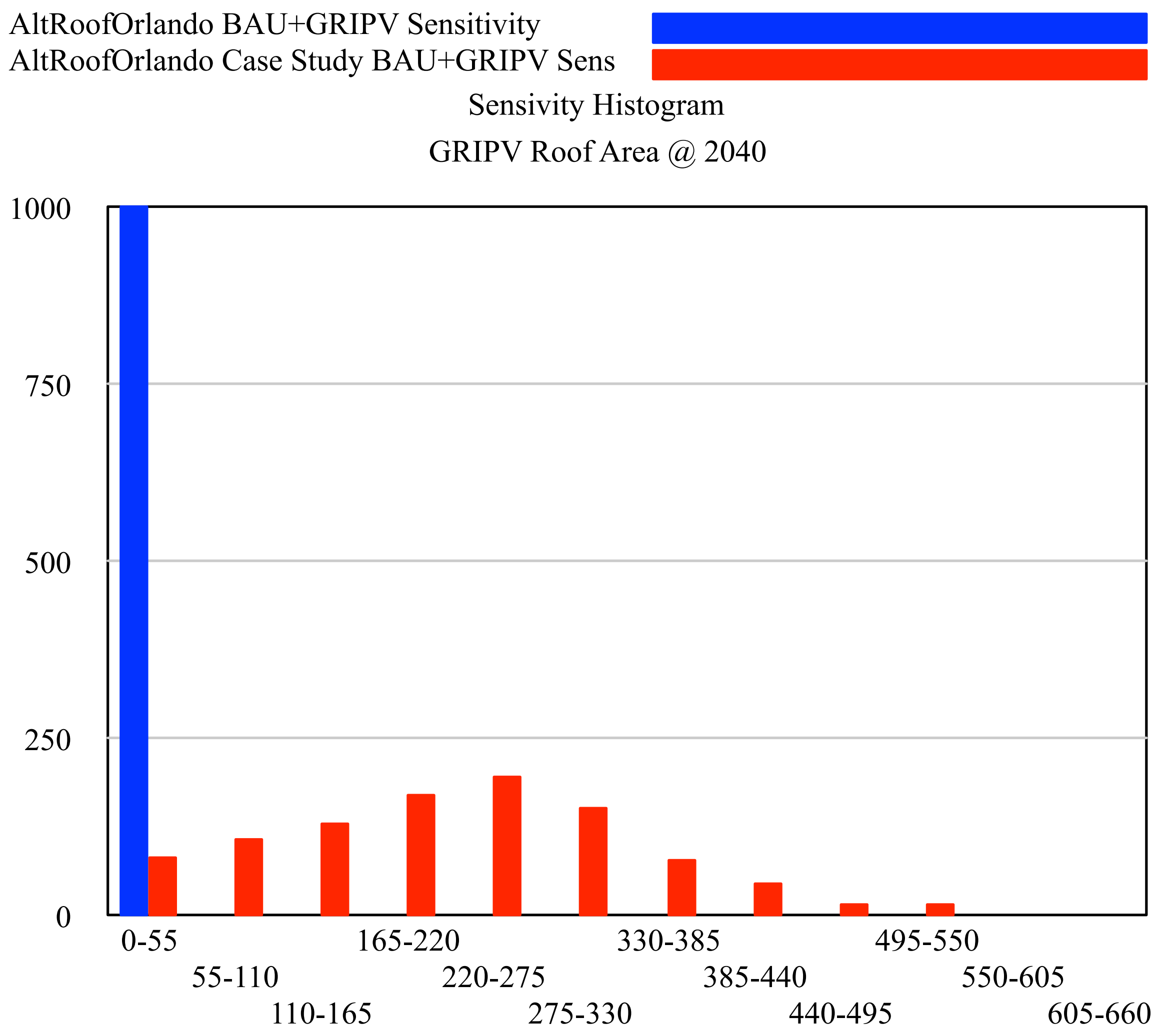


Figure K21: GRIPV Roof Area Case Study Histograms

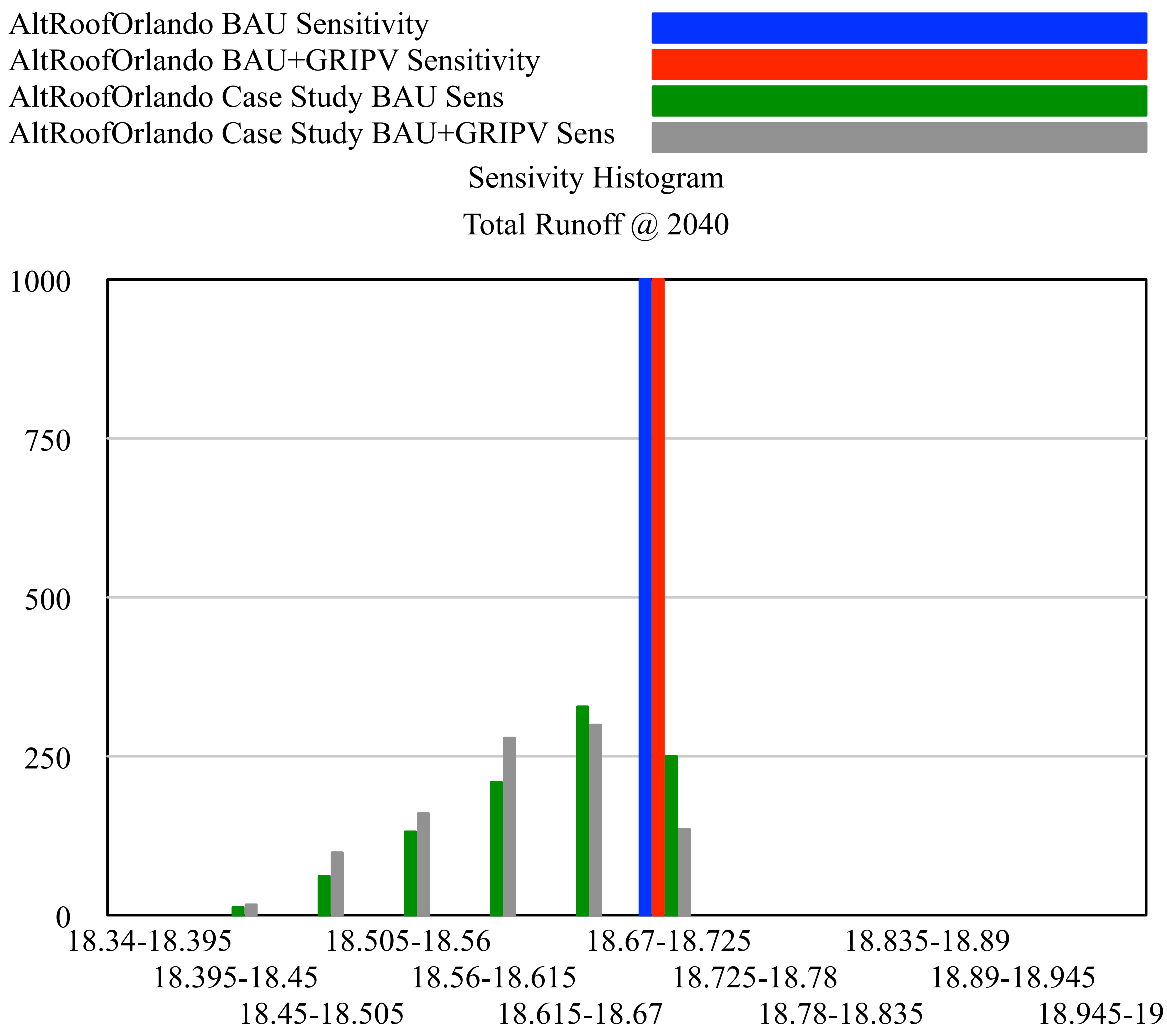


Figure K22: Total Runoff Case Study Histograms

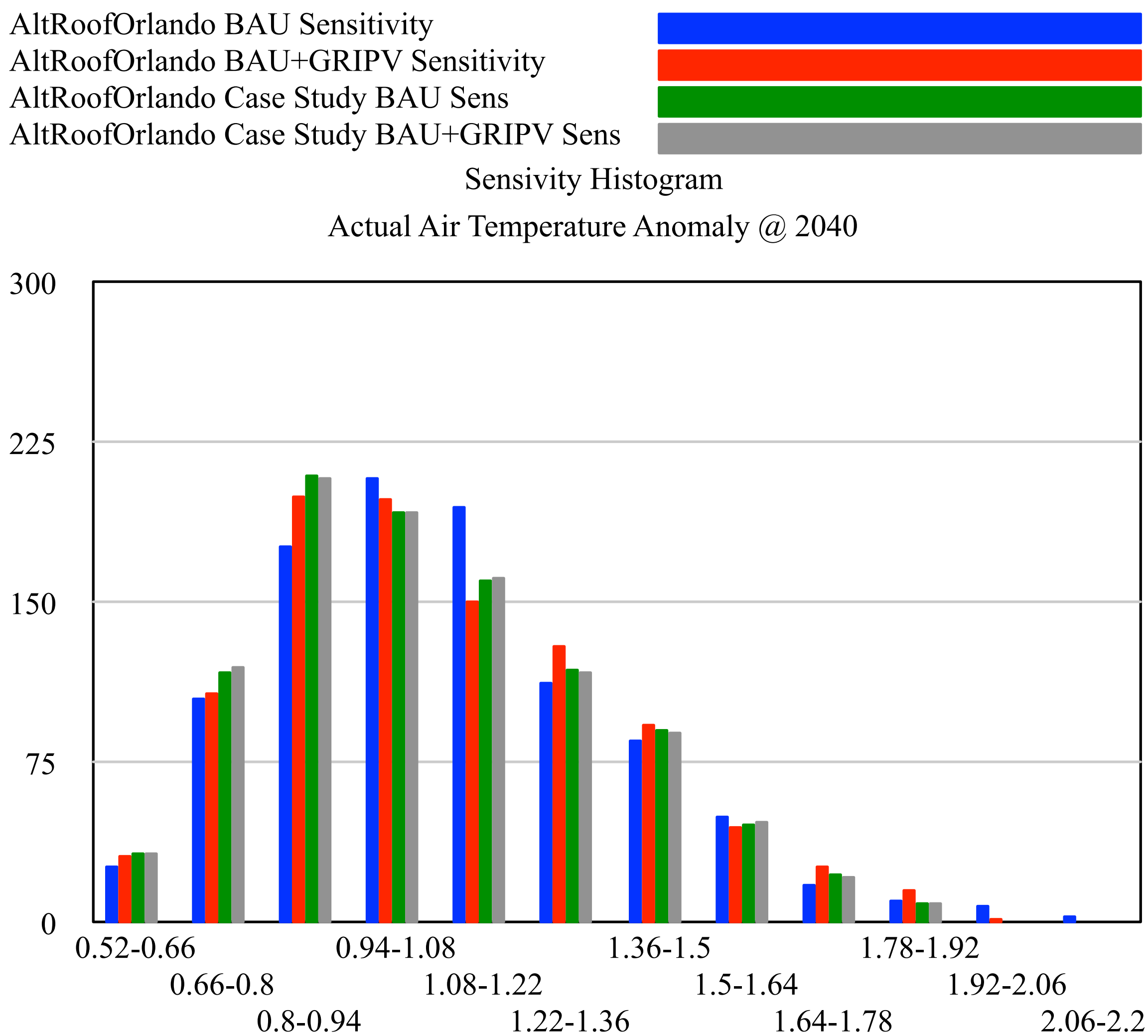


Figure K23: Actual Air Temperature Anomaly Case Study Histograms

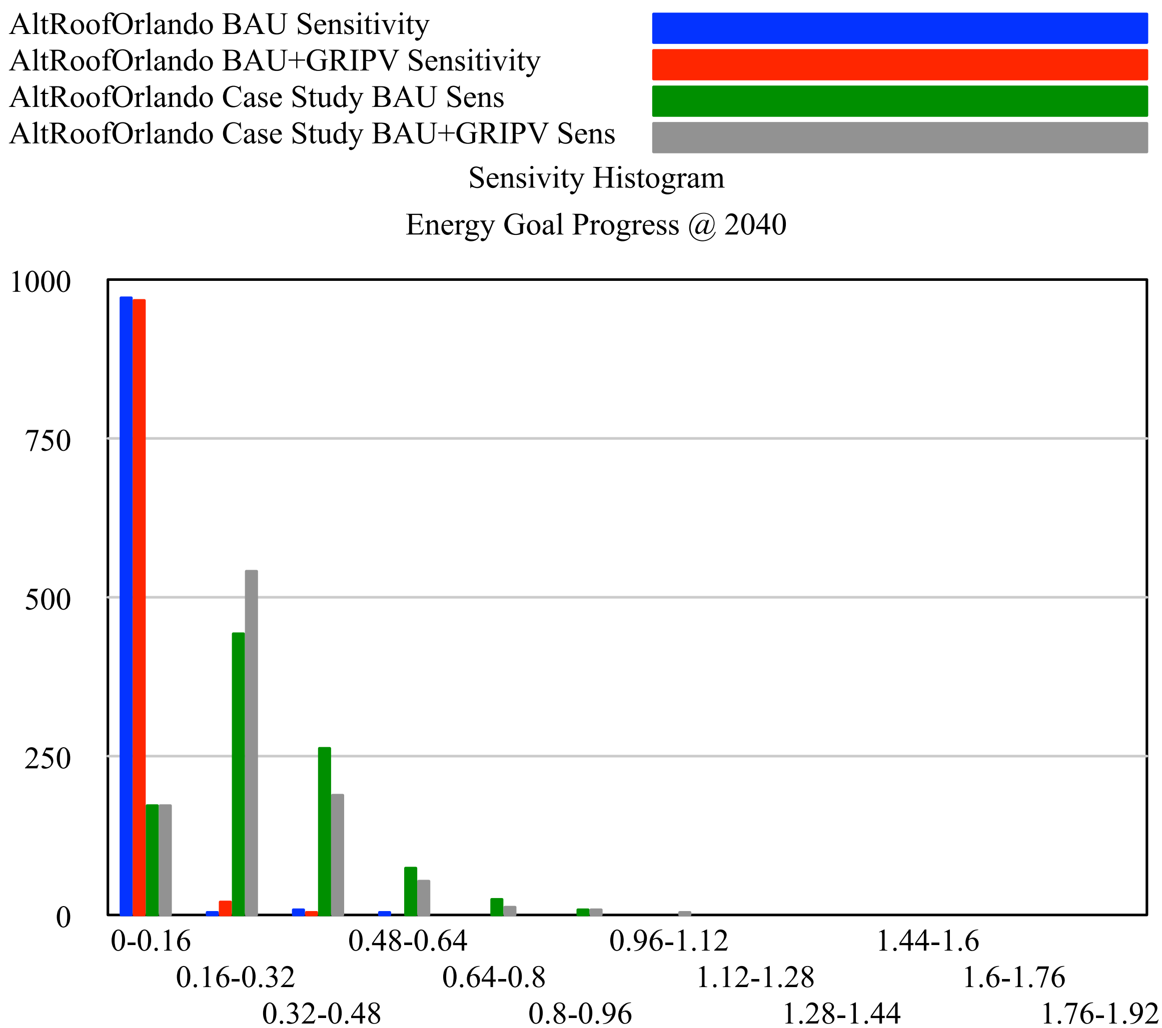


Figure K24: Energy Goal Progress Case Study Histograms

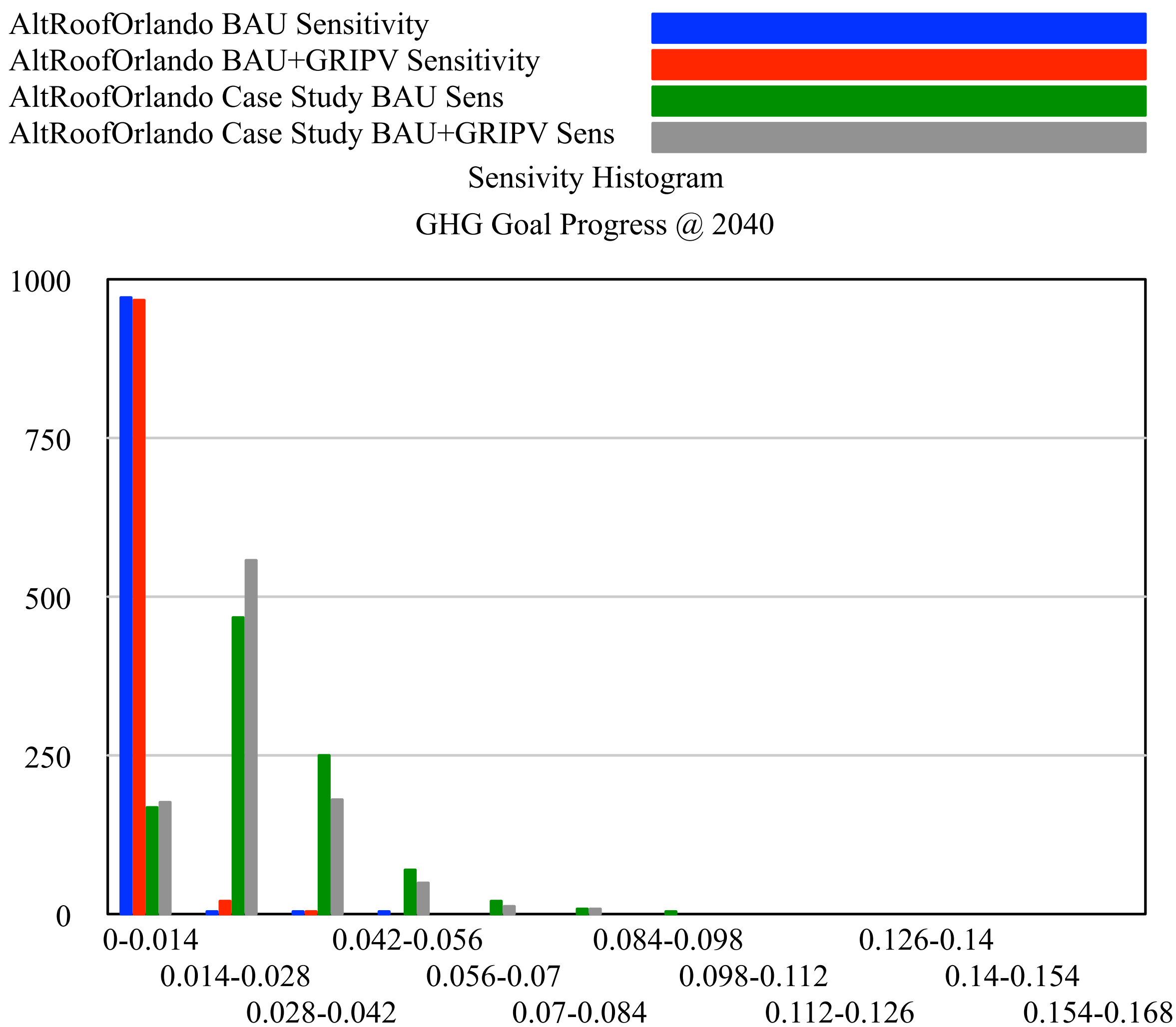


Figure K25: GHG Goal Progress Case Study Histograms

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